UPPER-LEVEL COLLEGE CHEMISTRY STUDENTS' CONCEPTS OF THE PARTICULATE NATURE OF MATTER

by

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INTRODUCTION

How do we know what we know and what is the basis for judging if what is known is correct? For as long as humans have been aware of knowledge, they have been theorizing about the process by which humans receive, process, and use information. The practice of discovering the nature of knowledge is documented as far back as the times of Plato. However, it was not until the nineteenth century when this practice came to be known by the term 'epistemology', stemming from a term coined by German philosophers, 'Erkenntnistheorie' [1]. The term is based on a translation of the Greek word 'episteme', which literally means 'knowledge'. Epistemology, the treatment of the subject of knowledge, began with the ancient Greek philosophers' perceptions that humans gain knowledge through their senses. The ancient philosophers were suspicious of information gathered by the human senses, however, because this information was severely limited to those events and objects that fell within the range of the senses. At best, this information was distorted because the senses report what is observed, which may not be representative of reality. The limitations of one's senses are demonstrated by the appearance of an oasis mirage observed in the desert or a square building which appears to the observer to be round in the far distance. These types of distortions were also seen as affecting the memory as well, because what is remembered is something that was observed and subject to the distortions of the senses. This belief of the limitation of direct observation is what led the ancient atomist Democritus to first propose that the senses yield no knowledge, or the knowledge formed was ambiguous at best The senses can detect changes that take place but can not explain why these changes take place. He sought to explain why changes took place all around. Greek philosophers of the time were intrigued by

his ideas that these changes sensed in the world could be understood through an explanatory principle that was not accessible to the senses directly. Democritus [2] employed such an explanatory principle when he suggested that certain observations made of objects and of changes can be explained by the idea of tiny indivisible particles of matter, which could not be directly observed by the senses. He concluded that something smooth and continuous, such as a stone, was a mere conglomeration of particles with a vast array of empty space in between. There is nothing that can be observed of the stone using the senses that can explain why it has the color it does or feels cool or warm to the touch. The "why" of these observable properties could be explained by properties of particles which lie beyond the limit of the senses. It is out of this line of thought, first born from philosophical study, that science has searched for various explanatory principles that lie beyond the scope of what can be directly observed by the senses. The theory of the particulate nature of matter (PNM) serves this explanatory purpose. PNM is a central concept in chemistry and pivots on the belief that all matter consists of individual particles and this core belief lends itself to an explanation of various observable phenomena such as changes in molecular connectivity, geometry, aggregation, state, and concentration. The explanatory power of this theory is also the basis of understanding for other chemistry-related topics such as acid-base reactions, electrochemistry, solubility, kinetics, and statistical thermodynamics.

As will be discussed in-depth shortly, learning in general and more specifically the learning about the particulate nature of matter is an individual process for each individual learner, because the meaning a learner assigns to concepts like PNM is based on individual variables. It is the individualized conceptions of PNM that are the subject of this study. It is widely accepted that the information relayed by an educator is not necessarily what is gained by the learner, and as such, learners often tend to form meanings of concepts that greatly vary from the educator's original intent [3-35]. An attempt is made by the science education community to expose the PNM conceptions formed by elementary, secondary, and college students during the learning process. A majority of these published

works tend not to focus on the whole conceptions of PNM, but rather focus on how learners' conceptions differ from what is scientifically accepted. These variant types of conceptions have been identified by several terms including alternative conceptions [33], misconceptions [18], preconceptions [36], and everyday conceptions [37]. What is not represented by the body of literature is the conceptions of PNM within the population of upper-level college students' and it is the hope of the author that the information presented here will begin the process of filling this void. This population is of interest because it serves as an indicator, when compared to the conceptions of other study populations, of how a learner's conceptions change over the course of advanced study. The information provided by this comparison can be used to affect the treatment of the topic of PNM during formal education. Only after alternative conceptions are identified among the student population is it possible to intervene to realign or adjust those conceptions to create a scientific knowledge framework.

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Cognitive Development Theories

Before being able to investigate and analyze the content and meaning of students' conceptions, it is first necessary to be familiar with theories that describe human cognitive development in order to understand how individual conceptions of PNM might form. It is through the lens of learning theories that a proper investigation into how an individual learns and the content of the resulting conceptions should be focused [38]. The theoretical basis for the current investigation is conceptual change which culminates aspects of several cognitive developmental theories, each important in understanding how humans acquire and retain knowledge.

A review of Thorndike's theory of connectionism and Piaget's theory of personal constructivism is provided to show the development of the idea that an individual's prior conceptions are important to the learning process. Piaget's theory also plays an important role in showing how the abilities for understanding PNM is directly related to a individual's cognitive level and demonstrates the process by which one conception, considered less desirable, can be exchanged for a more desirable one. The social aspects of learning are provided through a review of Vygotsky's theory of social constructivism and von Glaserfeld's theory of radical constructivism. The ideas expressed through the works of Thorndike, Piaget, Vygotsky, and von Glaserfeld are collectively known as constructivism and provide the basis of Ausubel's theory of subsumption and Novak's theory of education. Ausubel's theory extends the beliefs central to constructivism by introducing the concept of meaningful learning and Novak applies meaningful learning to the educational environment. Conceptual change employs both the

central belief of constructivism and like concepts found in subsumption and the theory of education.

The early Greek philosophers first pondered about what knowledge is and how close human interpretation could come to representing what reality is. The philosophical treatment of knowledge made a transition to the newer science of psychology as investigators began to take into consideration physiological processes that account for human cognitive development. The word cognitive as it is presented throughout this paper is meant to represent mental processes such as thinking, learning, remembering, and problem solving. Central to the process of cognitive development is the '*concept*' [39] which is a term used to represent some artifact of knowledge, the true definition of which varies according to individual learning theories. Through the following treatment of cognitive development theories, it will soon be evident that each theory treats the mechanism of knowledge incorporation somewhat differently. As such, a discussion is required of those theorist and theories which have provided fodder for the theoretical basis of this investigation, conceptual change.

Edward Thorndike [39] wrote of learning as a distinct relationship between stimuli and responses. According to Thorndike, a learner's knowledge is nothing more than an association or habit that is strengthened or weakened by the nature and frequency of the stimuli and response relationship. The central idea for his theory is trial and error learning in which certain responses come to dominate over others due to the rewards the response provides. Thorndike's theory, which is known as connectionism, was published in 1913 and influenced the way educators practiced until the mid 1960's. Although educators ceased subscribing to the theory directly, the central concept provided still influence developing cognitive theories. Connectionism has three primary laws: (1) Law of effect- responses to a situation which are followed by a rewarding state of affairs will be strengthened and become habitual responses to that situation. The essence of the first law is still practiced by many current educators in hopes of reinforcing good ideas and behaviors. (2) Law of readiness- a series of responses can be connected together to accomplish some goal which will result in personal

irritation if blocked. Good grades are the goals of students and if concepts are not recalled during examination, bad grades and thus irritation are the results.
(3) Law of exercise- connections become strengthened with practice and weakened when practice is discontinued. Students are given homework to strengthen the concepts learned at school.

A corollary of Thorndike's law of effect was that responses that reduce the likelihood of achieving a rewarding state would decrease in strength. The theory suggests that the transfer of knowledge depends on the occurrence of identical elements in the original and new learning situations; i.e., transfer of knowledge is always specific, never general. This means that, to the learner, there must be some content of familiarity in the new learning situation in order to allow a connection to be made between the two events. Thorndike later updated his theory to introduce and include the concept of 'belongingness': connections are more readily established if the person perceives that stimuli and responses go together. This reemphasizes Thorndike's belief that a connection is made between the new and old learning events. Thorndike's theory is important to this discussion because it provides for the idea that in order for new knowledge to form, connections are required with knowledge that has already resulted from previous experiences. It was this idea, existing knowledge, that provides the basis for the theory of Jean Piaget, although the described mechanisms of obtaining knowledge are quite different.

Jean Piaget is widely considered to be one of the greatest child psychologists of all times. His ideas are present in almost every child development textbook and are taught in psychology courses worldwide [40]. What is surprising is that Piaget did not consider himself a psychologist at all because he was not interested in predicting his subjects' behavior. It is reported that he instead thought of himself a genetic epistemologist, engaged in the science of how knowledge is acquired [41]. Piaget was a trained biologist, receiving a doctorate in 1918 with a dissertation on mollusks. It was this training that greatly influenced his conceptualization of cognitive development: he saw intellectual development much as he saw biological development. Cognitive acts, the events

that lead to the incorporation of new knowledge, happened for either organizational or adaptive purposes. Cognitive events can not be separated from the total functioning of an organism; therefore, Piaget treated cognitive activity as a special case of biological activity. According to Piaget, cognitive activity and biological activity are both responsible for the overall process by which an organism adapts to the environment and organizes its experiences. Piaget used four concepts to explain how and why cognitive development occurs: schema, assimilation, accommodation, and equilibration [40-42]. A schema is a structure within the mind which provides an ability to adapt cognitively to the environment. Schemata (pleural of schema) are the mental equivalents of physical biological means of adaptation (change in color, size, etc.). Schemata are not viewed as physical structures like an organism's nervous system, for example; rather, they represent the neurological activity process that lead to the incorporation of information into an organism. Simply stated, schemata can be thought of as concepts or categories. An analogy might be folders contained in a filing cabinet. Individuals have many folders containing various knowledge used to process and identify incoming stimuli. As folders are added to the filing cabinet, the information contained in the filing cabinet becomes more refined. What was first filed as specific pieces of information resulting from specific stimuli can now be applied to an ever-increasing amount of incoming stimuli, making the information contained in the schemata generalizable to the individual. As an example, imagine a child in the kitchen with her mother while she is preparing dinner. The mother holds up a cucumber and asks the child what it is. The child, faced by a new stimulus, as she have never seen a cucumber before, searches the filing cabinet for the appropriate file containing information on round green objects that are edible. The child replies that it is a small watermelon, resembling the one the family enjoyed on the Fourth of July. The fact of "watermelon" represents an established schema that was accessed by the child when faced with something that is new and unfamiliar. Schemata are cognitive structures that are used to organize events as they are experienced by organisms and classified into groups by means of comparable characteristics. Schemata do

change, therefore it is reasonable to account somehow for their growth and development, just as a newborn eventually grows and develops into an adult. It is apparent that adult's concepts are different from those of children. The processes responsible for the growth, development, and change are assimilation and accommodation [41].

Assimilation is the cognitive process by which a person incorporates new information into existing schemata. To continue the filing cabinet analogy, as new conditions (stimuli) are experienced, there is an addition or change made to the information contained in a folder (schema). When the mother holds up the cucumber and the child does not recognize the vegetable, the information is added to the schema (a folder) called "green objects we eat " which contains information about watermelons. The object, cucumber is assimilated into the "green objects we eat" schema. Assimilation takes place continuously as human beings are faced with processing increasing numbers of stimuli. Assimilation does not result in the changing of schemata, but rather is responsible for the growth, i.e. in the example, more green objects we eat. It is like a folder in the filing cabinet growing larger as more paper containing information is placed within it: the folder itself does not change shape, only grows larger.

Piaget accounted for the changes in schemata, the folder, by describing accommodation. Accommodation occurs when assimilation is not possible. Sometimes stimuli are experienced and can not be placed or assimilated into a schema because there is not one in which the new information readily fits. Continuing the cucumber example, why is one green object we eat red inside and the other is not, yet they both have seeds but taste quite different? At this point one of two events is possible: (1) A new schema (folder) is created to house the new information or (2) an existing schema is modified so that the information will fit. The meaning of accommodation [41] is either the creation of new schemata or the modification of old schemata. Using the file folder analogy, either the folder would grow larger because of new information placed within or an entirely new folder would be created to store the new information in. Both result in the development of new or different cognitive structures. Once

accommodation takes place, a person will again try to assimilate the new information. Because the structure has now changed, and there is now an existing schema (folder), the information will be readily assimilated. In this way, assimilation is always the end product of cognitive development. Schemata reflect the person's current level of understanding and knowledge of the world. Schema can be seen as a construction that takes place over time. Since the schemata are constructions, they do not accurately portray reality. As a person develops from the infant stage to the adult stage, the structures of their experiences in the form of schemata do approach reality in appearance. Together assimilation and accommodation account for intellectual adaptation and the development of cognitive structures. Of equal importance is the balance between assimilation and accommodation that needs to take place for typical cognitive development. If a person only engaged in assimilation, the results would be few but very large schemata, i.e., one schema with all of the food that we eat. If a person only engaged in accommodation, the results would be a number of very small schemata that would result in a loss of generality, i.e. food with seeds, food without seeds, but would not know that vegetables are food that can both have seeds or not. In either case, the result would be abnormal intellectual growth. Piaget described [41] a balance between assimilation and accommodation as equilibrium. Equilibrium is simply a balance that is self-regulatory, that must exist between assimilation and accommodation. A similar idea is disequilibrium, which is the state of imbalance between assimilation and accommodation. Equilibration is the process of moving from disequilibrium to equilibrium. The process of equilibration is what allows external experiences in the form of stimuli to be incorporated into internal structures (schemata). As a person strives to achieve equilibrium, they will assimilate all external stimuli with or without accommodation. The end result is that everything must be assimilated by a person. The schemata that a child would use may not necessarily be in accordance with schemata that an adult would select, but the child's placement of stimuli into schemata is theoretically always appropriate for his or her level of conceptual development. There is no wrong placement. There is improvement

in the placement as intellectual development proceeds. As a person, upon experiencing a new stimulus, assimilates that stimulus into an existing schema, equilibrium is attained for a moment relevant to the particular stimulus event. If a person cannot assimilate the stimulus, he or she then attempts to accommodate by modifying a schema or creating a new one. When this is done, assimilation of a stimulus proceeds and equilibrium is reached only for a moment. Therefore, assimilation and accommodation, and the balance thereof, in the process of equilibration, account for the growth and development of cognitive structures and knowledge. In the same sense as organisms adapt to their environment through physical change, the development of the mind's intellectual development is also a process of adaptation.

It is seen because the schemata present in children changes over time, then the schemata present in adults would seem to be more complex. Piaget conceptualized development as a continuous process along a continuum. Changes that take place in cognitive development are slow and never abrupt. Schemata are constructed and reconstructed gradually. The schemata network increases in complexity as a result of personal development and growth. To conceptualize this cognitive growth and the increase in cognitive complexity, Piaget formulated four broad stages of cognitive development [39-41].

The Stage of Sensory Intelligence (0-2 yrs). During this stage, behavior is primarily responsive and motor. The child does not yet internally represent advances in thinking conceptually, though cognitive development is seen as schemata are constructed. For the first year and a half or two years of life, infants are only aware of sensorimotor experience, and do not connect it to things outside of themselves. They do not know how things will react, and so are always experimenting -- shaking things, putting them in their mouths, throwing -- to learn by trial and error. At this stage, schemata are said to be reflexive in nature.

The Stage of Preoperational Thought (2-7 yrs). This stage is characterized by the development of language and other forms of representation and rapid conceptual development. Reasoning during this stage is pre-logical or semi-logical.

The Stage of Concrete Operations (7-11 yrs). During these years, the child develops the ability to apply logical thought and concrete problems.

The Stage of Formal Operations (11-15 yrs or older). During this stage, the child's cognitive structures reach the greatest level of development, and the child becomes able to apply logical reasoning in all cases and problems.

Piaget did not suggest that children move from discrete stage to discrete stage in development, as if one leads from one step to another while walking the stairs. Rather he believed that cognitive development flows along a continuum in a nonlinear manner: each new step of development builds upon and becomes integrated with previous steps.

Piaget's theory of intellectual development should not be viewed as a permanent fixture set in concrete. All psychological theories, like humans, are organic and thus continuously change. Like most theories, Piaget's theory is not complete. At this time it remains a description of cognitive development. The theory contains clear thoughts about why and how development proceeds, but how the mechanisms involved in development work is not fully clear. As such, Piaget's theory does not completely explain the process of cognition and therefore, is a primary reason that only the central ideas have been pulled into the broader theory that is constructivism.

Piaget [43] believed that knowledge is acquired as the result of a lifelong constructive process in which we try to organize, structure, and restructure our experiences in light of existing schemata of thought, and thereby gradually modify and expand these schemata. The keyword in this phrase is constructive, which reflects the ideas of the constructivist model. The constructivist model has

at its core two fundamental beliefs. 1) Knowledge is formed in the mind of the learner, and 2) There is no knowledge independent of the meaning attributed to the experience by the learner or community of learners. Bodner states that Piaget was perhaps the first constructivist in the sense that a view that knowledge is constructed in the mind of the learner was based on research on how children acquire knowledge. Bodner raises an interesting point when asking the question if individuals construct their own knowledge, how can groups of people appear to share common knowledge? The answer lies in the fact that knowledge incorporated into a learner's cognitive structure will somehow fit the perceived reality. Construction is a process in which knowledge is both built and continually tested. Bodner in a later paper [44] shows how the idea of constructivism has taken on many forms. He suggests that the form of constructivism that grew out of Piaget's model of cognitive structures should be called personal constructivism. The reason for this is that knowledge is something that is constructed by the individuals to meet their own needs. As will be discussed shortly, Piaget's model of personal constructivism will serve as the basis for much of the work that is done in conceptual change, which involves the development of learning experiences that helps students through the process of making large scaled changes in their understanding of the concept. Another relevant type of constructivism is radical constructivism. This theory is associated with the work of Ernst von Glaserfeld, who bases his view of constructivism on two principles. First, knowledge is not passively received, it is actively built by the individual, and second, the goal of cognition is to organize our experiences of the world by making those experiences meaningful. Piaget's influence can be seen by making a comparison of the second principle with Piaget's idea that as biological systems, we use cognitive constructs to organize our world or environment. A third type of constructivism, based on the works of Lev Vygotsky, is social constructivism [39]. Lev Vygotsky focused on the social aspects of learning. Cognitive growth within social constructivism requires interaction with other minds. Without society and the interaction provided within society, knowledge forms, but is extremely limited. Bodner brings this point to

the surface by suggesting that by focusing on the individual learner, the personal and radical constructivist theories seem to neglect or ignore the ways in which social interactions influence the process by which knowledge is constructed.

The processes by which students go about trying to make sense of the world in which they live is also influenced by society in an additional way. Sense making by individuals in social contexts has been of particular interest within the social sciences and is investigated and described by a specific area of the sociology known as Ethnomethodology [45]. Ethnomethodological investigation into social interaction is useful in demonstrating the ways people form and employ bodies of common beliefs, generally described as "common sense" to guide social interactions. It is through a similar process people come to form a "common sense" approach when interacting with and engaged in sense making of the scientific world. In general, as students go about their daily lives and encounter a variety of situations, whether in or out of the classroom, they will try to make sense of them by employing their established common sense knowledge. As a result of this process, the newly established concepts may ultimately represent something other than the original scientifically accepted concepts. The overarching role of the conceptual change model in science education is to provide a pathway for learners to achieve correct scientific understanding, and the different types of constructivism discussed thus far provide a foundation. Personal constructivism established the belief that learning is an individual process. Radical constructivism added the belief that learning is not a passive event. Social constructivism draws on the belief that although knowledge building is an individual process; it does not take place unless there is adequate social interactions. Conceptual change beliefs, therefore, have not been created independently, rather draw upon many cognitive development models.

Driver et all [15] provides an outline of current constructivist views of learning that is worth repeating here as it serves as a basis for the current learning theory employed by this study. To begin, learning outcomes rely on both the learning environment as well as what a learner already knows which is influenced by "common sense". "Students' conceptions, purposes and motivations directly

influence the way they will interact with learning materials in various ways". "Learning involves constructing meanings"; learners will construct meanings from experiences by generating links between their existing knowledge and new phenomena. Construction of meaning is a continuous and active process; learners continuously and actively link new information with existing knowledge. "Learners are responsible for their own learning…", regardless of intent of the educator. Learners have to exert the effort toward the learning task, actively relating to their prior knowledge and evaluating the meaningfulness of the newly acquired information. It is also important to recognize that although constructivism is seen as an individual process, certain resultant knowledge is shared among a group of individuals. It is the process by which meanings of concepts can be based in scientific meaning and shared among a group (body of students) that is of interest to the educational community.

Another outgrowth of Piaget's cognitive development theory was the theory of subsumption, introduced by David Ausubel. Ausubel was very active in the field of psychology in the 1950's through the 1970's and developed his instructional models based on cognitive structures. Ausubel's theory is involved with how individuals learn large amounts of "meaningful" material from verbal textual lessons in school. This is in contrast to theories developed in the laboratory. At the very heart of Ausubel's theory, was his idea that the most important single factor influencing learning is what the learner already knows [46]. The key concept to his theory, which is meaningful learning, has infiltrated the science educational community. There are several theories that will be discussed shortly, which make use of meaningful learning. What is meant by meaningful learning? According to Ausubel, it is attainment of meaning that necessarily reflects the completion of the learning process. Mayer [22] provides additional clarification of what meaningful learning means: " [meaningful learning] is a distinction between the overall amount of information remembered and how many associations have been made to other existing concepts". In other words, simply remembering bits of information does not constitute meaningful learning. In order for information to be learned in a meaningful way, aspects of new concepts, information or

situations must be connected with relevant components of existing cognitive structures in various ways.

Bretz [47] provides a description of a theory that is gaining a wide body of acceptance in education, Novak's theory of education which combines ideas found in constructivism and the idea of meaningful learning. Much of Novak's theory follows the central constructs of Ausubel, both being that central to the learning experience is meaningful learning. According to Novak's theory, in order for knowledge to have meaning for the learner, three conditions must be satisfied:

- A student must have some relevant prior knowledge to which the new information can be related in a non-arbitrary manner. These resembling connections must be made within the schemata in order for assimilation and accommodation to take place in Piaget's theory.

- The material to be learned must be meaningful in and of itself; that is, it must contain important concepts and propositions relating to existing knowledge.

- A student must consciously choose to non-arbitrarily incorporate this meaningful material into his or her existing knowledge, a disposition which Ausubel labels as the meaningful learning set [46].

What is unique to the Novak's theory is that meaningful learning must occur across three domains of personal experience. These three learning domains are cognitive, affective, and psychomotor. The cognitive learning domain involves the mental aspect of the learning process and is where much of the prior theorists' attention is invested. The affective domain involves the attitudes and motivations of the learner. The psychomotor learning domain involves physical experiences. According to Novak's theory, in order for meaningful learning to occur, a learner must experience stimuli that influence all three domains, and without these stimuli, cognitive development does not take place.

The theoretical basis for this study is that of conceptual change, as described by Posner et al. [48]. Conceptual change is a culmination of the previously described theories. The authors state that merely "identifying misconceptions...and understanding some reasons for their persistence, falls short of developing a reasonable view of how a student's current ideas interact with new, incompatible ideas". In their view, Piaget was successful at developing on such theory, however, the Piagetian theory does not provide an explanation or description of the "substantive dimensions of the process by which people's central, organizing concepts change...under the impact of new ideas or new information". Like Piaget's personal constructivism, conceptual change uses the concepts of assimilation and accommodation. Assimilation in conceptual change is used to define those instances when existing concepts are used to deal with new phenomena. For example: students using the concept of moving atoms in a gas to explain the concept of pressure. Accommodation is the event when existing concepts are inadequate to allow new concepts to be obtained successfully, which in turn requires replacement or reorganization of existing concepts. An example would be students who are asked to explain heat energy transferring through a material when the students only have a concept about moving atoms in a gas. Key to the conceptual change theory is the conditions under which accommodation takes place. Central concepts that exist in the mind of the learner are usually judged as personally valuable not on the ability to correctly generate predictions but rather on the usefulness for solving immediate problems. These central concepts are likely to be rejected when they no longer provide to be useful in this way, and consequently, accommodation takes place. Posner et al. list four conditions which must be met in order for event of accommodation to take place:

- ***There must be dissatisfaction with existing conceptions.*** Learners are not likely to replace a concept unless it no longer works. This condition is reflective of the constructivist belief of the importance of pre-existing knowledge and how unless the educator is aware of existing conceptions, there is no way to get the student to the scientific conception.

- ***A new conception must be intelligible.*** "The individual must be able to grasp how experience can be structured by a new concept sufficiently to explore the possibilities inherent in it." Central to this condition is the idea of meaningful learning, a belief touted by Ausubel and echoed by Novak, where the learner has to have an appreciation of the new concept or how the commitment to new information can alleviate frustration of not understanding.

- ***A new conception must appear initially plausible.*** The new concept must at least appear to have the possibility of resolving the situation created by the old concept. The new concept must also be compatible with other existing concepts. This condition relies on the initial process of sense making by the individual, because knowledge is constructed and must be meaningful, an attempt is made to form links between the new information and existing information.

- ***A new concept should suggest the possibility of a fruitful research program***. "It should have the potential to be extended, to open up new areas of inquiry".

The conditions are linked through ideas of constructivism and meaningful learning. The ideas presented here are important because they present a path for selectively changing students' conception to better scientific understanding, the goal of the educational experience. It also presents evidence for why students' existing PNM concepts are important for educators to know and understand. In order to successfully change students' conceptions, according to the conceptual change model; we must first know what those concepts are.

Learners' development of PNM concepts

Science educators and science education researchers alike recognize the particulate nature of matter (PNM) as being one of the most important concepts for students to understand [7, 17, 18, 49, 50]. A common theme found within the literature reviewed is that the physical science concepts are easier to learn and comprehend if students first have good concepts of atoms and molecules and can apply these concepts properly when explaining various phenomena. To investigate what PNM concepts are in place when as students study a variety of topics in physical science, a variety of research has looked at what students at different age groups believe. The conceptions of children (primary and elementary school age) [14, 21, 30, 51-55], middle school-aged students [19, 56], junior-high [3, 50, 57] , secondary [3, 10, 25, 49, 50, 58-60], introductory-level college [3, 50, 61-63], and graduate-level college [64, 65] have all been reported in the literature. Conceptions of PNM have been reported for upper-level college (beyond introductory and intermediate levels) [17], however, this study reports conceptions of pre-service science teachers and does not focus on the PNM conceptions of chemistry majors. Presented here is a review and discussion of findings from research focused on students' conceptions of PNM. The research is provided in order to show how PNM concepts change with age, and thus development levels. Preservice teachers' conceptions of PNM are also discussed, as these are the people directly affecting what students believe and how they come to believe what they do about PNM.

A point that needs to be addressed before discussing the first study is that there is a different treatment of PNM for students at earlier ages in accordance with Piaget's ideas about developmental levels. Students at the younger grades, between the first and fifth, are taught a distinction between matter and nonmatter, and this information serves as a basis for learning about atomic and molecular makeup of matter during more advanced study. Children at the younger ages are not developed cognitively to a point where they can process the abstract information contained in PNM concepts. Marin and Benarroch [66] suggest

through a review of research that it is not until around the age of ten that children begin to use particulate concepts. Therefore, a look at young children's concepts will focus not on PNM concepts, but rather the foundational concepts of matter/ non-matter distinction.

Ruth Stavy [54] conducted research on young children, ages 6-13, to determine what the conceptions of matter were among students at this age level. Her methodology was to ask students from Tel-Aviv area schools in grades 1, 3, 5 and 7 to classify materials and phenomena as being composed of matter or not. Her sample population included twenty students from each grade level. The students were interviewed while being shown the materials and phenomena. During each interview session, the students were asked to explain what matter was, and then they were shown a series of material and nonmaterial objects and phenomena and asked to classify each. Examples of material (matter) were rigid solids such as a piece of wood and iron metal. Non-rigid solids included cotton wools and a metal spring. The solids also included powders like sugar and flour; liquid examples (mercury, milk and water) and a gas was represented by room air. Non-material (nonmatter) examples included smell, fire, electricity, wind (as movement of matter, air, not the air itself), heat, light and shadow. The examples were provided to the students in a concrete manner by showing the students examples of each. It is implied by this approach that students at this age would be at the concrete stage of cognitive development, although she does not state this directly. Responses to the first question, what is matter, were classified into five categories. The author points out that the majority of the students at all age levels were able to explain what matter was. The most prevalent response from students in grades 1 and 3 was an explanation by means of example rather than the students providing reasons. Examples provided by students included materials like clay, glue, cleaning materials, and building materials. All grade and age levels demonstrated the remaining 4 categories:

- Explanation by means of function
- Explanation by means of structure
- Explanation by means of properties,
- Other kinds of matter, usually learning materials, reading materials, etc.

The latter two categories were almost exclusively demonstrated by the older children, fifth and seventh graders, and revolved around their ability to provide specific properties of matter such as hardness, tangibility, color, etc. These students could also recognize states of matter as solid, powder, etc., and could describe properties associated with weight and volume. Stavy summarizes the responses to the first question by saying that younger children tend to verbally explain matter by giving examples of typical materials and do not normally define features. As children grow in cognitive ability, they begin to also think about matter in terms of structure and properties, but in the end, only 10% of 7^{th} graders can relate the properties of weight and volume, which the author states are relevant in scientific context. Stavy then provides an analysis of the students' ability to classify materials and phenomena as matter and nonmatter. Her overall findings are that most materials are identified correctly as matter, with increasing ability coming with increasing age. The problematic area came from biological materials that were correctly identified as matter less than 50% of the time. Most examples of nonmaterials were correctly identified as nonmatter; however, younger students had the most trouble (< 30% correct) identifying heat and light as nonmatter. The author's suggestion for findings of this study is that during grade advancement, there is a shift in instruction from a classification pattern to what is more accepted as the scientific definition of matter. She says, however, that there is a lag of students' ability to define and describe matter in terms of what is more scientifically accepted. In general, students' ability to classify matter and nonmatter leads to their ability to define and describe matter and nonmatter. The author suggests that the implications for education are that the particulate nature of matter cannot be taught if students do not know what matter is. She suggests that teachers should spend time discussing and clarifying the

meaning of matter before moving on to PNM issues. She also suggests that teachers should start with examples that students recognize as matter and move to those that they have demonstrated difficulty understanding, namely gases, as being constructed from matter and having particulate nature. For the conceptual change model, this would suggest that students should be made aware of how their conceptions of matter and non-matter fit in with what is scientifically accepted and presented with situations where the students definitions of each do not work so that they will search for a newer, better conception that is more in line with scientifically accepted definitions.

It can be inferred from Stavy's research that since children have difficulty with the concept of matter that they would also have difficulty describing what the particulate nature of matter is in scientifically acceptable terms. Roger Maskill et al. [21] set out to find out if students aged 11 and 12 years have a concept of PNM and if so what that concept is. Identifying prior knowledge is a necessary step which must be accomplished before being able to present situations in the classroom that will lead to conceptual change. This is especially true when meeting the first condition of conceptual change by providing learners with situations that cause dissatisfaction with existing concepts. The Maskill et al. study takes place at the time students in this age range begin formal learning of science in school. Their premise for the study was that students by this age have not had formal instruction involving PNM, and therefore any description the students provided would be based on everyday learning versus formal scientific instruction. The authors used students from three different European countries- Greece, Portugal, and the UK. The study group included 100 students from each country from randomly selected mixed ability schools, representing both urban and suburban environments. The only significant difference between the three countries is that the Greek students had received formal instruction on the particulate nature of matter before the study commenced. The authors choose to use a tool called the word association test to test students' conceptions because this particular tool is sensitive to cultural designations in the meetings of equivalent words when translated into different languages. In their application of

this test, the students were given a booklet containing the stimulus words to be tested in sentence form and had one minute to write down words associated with each stimulus word. All of the words were chosen for their ability to prompt both particulate and not-particulate ideas. "The sentences were chosen to relate the words to the notion of substances, their properties, and their makeup, without suggesting the need to focus on the particulate model. The purpose of the test was to probe the extent to which the pupils spontaneously relate to particulate model to what they know about the substances they are familiar with all around them." The test was set up so that all the words used on the test could be responded to using non-particulate ideas. The students were given a booklet containing the stimulus words to be tested in sentence form. The students were given a minute to write down as many words associated with the word being tested.

The authors provide specific analysis to each of four categories tested: States of Matter, Classes of Substances, Changes in Materials, and Particles of Matter. The stimulus words used for "states of matter" were "solid," "liquid," "gas," and "matter." In general, students responded by providing examples of stimulus words, for instance would give an example of a solid rather than indicating "solid". Only in the Greek population was there evidence of the particulate model. Students from Portugal and the UK did not mention atoms or molecules or particles in their responses. For "classes of substance," the stimulus words were "element," "compounds," and "chemicals." In responses to the three stimulus words, country specific meanings were provided, showing that language has some influence as to the meaning of the words. Again, only Greek students used terms associated with a particulate model. The next category, "Material change" used the stimulus word "reaction." The vast majority of responses, other than Greek, showed no evidence of scientific meaning for this word. Instead, the dominant meaning provided was placed in terms of human reaction, either physical movement or feelings. The last category "Particles of matter" used the stimulus words atom, molecule, and particle. The overall results for this category were that "the particle idea are present by not very strongly." The authors then

provide discussion about the differences in meaning for each of the stimulus words based on country of origin. They admit to a language barrier persisting through the analysis of the data they collected from the three countries. Consequently, they suggested that an interesting experiment might be to test students before and after they are taught about PNM, in the same country. Their overall conclusion is that indeed students build everyday meanings for PNM concepts; however, it is greatly dependent on the culture of the students. The word atom and molecule, even though at the root of PNM concepts, have different meanings for students of different countries and cultures. In gist, PNM has a different meaning depending on where you are a student, even though PNM concept are universally accepted in the scientific community, regardless of the nationality and cultural upbringing of scientists. The question then arises, if students are able to form everyday concepts of PNM without formal instruction, how do they internalize formal instruction concerning the particulate nature of matter?

Shimshon Novick and Joseph Nussbaum [57] sought to answer this question with research they conducted on 13-14 year olds in Israel who had completed the first year of formal science study. The focus on this instruction was the three states of matter, and investigation of selected characteristic properties (i.e. density, fluidity, compressibility, dysfunction, crystallinity, decomposition, and mixing) in terms of a simple particle model. The study population was drawn from disadvantaged, nondisadvantaged, and mixed ability eighth grade classes from nine urban schools. The authors do not discuss the exact number of participants, however, n= is reported as being between 136 and 154 for the responses identified. Student understanding of five aspects of PNM were probed:

- A gas is composed of invisible particles
- Gas particles are evenly scattered in any enclosed space
- There is "empty space" between the particles in a gas
- Particles in a gas are in intrinsic motion-they are not pushed externally
- When two different substances interact to form a third substance, we picture this as the "joining" together of different kinds of particles.

Data were gathered during interview sessions lasting 30 minutes or less. The results show that students at this level do not "internalize important aspects of the particle model." Instead, students have a continuous picture of gases and phenomena surrounding chemical reactions and changes in matter. The author suggests that this is because prior to starting formal science instruction, the students internalize a continuous model of matter, because it is what seems to explain logically characteristics that are observable. In order for the students to internalize abstract particulate nature of matter concepts, they must abandon the continuous model, and because the continuous model is taught in a logical sense, students are apprehensive to this change. As a result, the authors suggest that students need "practice in observation and interpretation of dissonant phenomena", similar to the concepts presented in their research. They believe this would lead to "greater accommodation by more pupils to the particle conception of matter. According to the conceptual change model, this would not be enough to cause students to gain correct particulate conceptions. The conceptual change model suggests that in order for the correct particulate knowledge to be acquired, it has to offer an explanation of the phenomenon, as well as, be logical to the learner. This study was conducted in the late 1970's and led to authors into a broader study of student conceptions of PNM.
In what has become a classic publication and serves as a foundation for many similar studies on the particulate nature of matter, Novick and Nussbaum [50] again investigated concepts of PNM, however, broadened the investigation to include elementary, secondary, and introductory university students. They set up this research by stating, "pupils are generally introduced to the particle model of

matter in junior high school. Further exposure to the model occurs through the high school years in most school science courses. It is therefore reasonable to expect that pupils' understanding of basic aspects of the model should increase as they progress..." The authors repeat their assertion from their 1978 study that the more cognitively demanding a concept is, the more likely it is that the student will not internalize it. Therefore, the current study concerns itself with aspects of the particle model that are viewed as being increasingly demanding:

- Gas particles are uniformly distributed in a closed system
- Gas particles are in constant motion
- Heating and cooling cause changes in particle motion,
- Liquefaction is viewed as a change in particle density,
- There is empty space between the particles in a gas.

Because the targeted student population was too large for an interview approach, the authors developed a new tool to ascertain student conceptions. This tool is the Test About Particles in a Gas (TAP). "The test consists of nine items, each involving a phenomenon, a simple experiment, or a situation. Subjects were asked to (a) complete a drawing; (b) write an explanation; or (c) choose among a number of given explanations or drawings." The subject population consisted of students from elementary grades 5-6 (n=83), junior high grades 7-9 (n=339), senior high grades 10-12 (n=88), and students from university sophomore level (n=66). The responses to the TAP were divided according to the grade level. For item 1, gas particles are uniformly distributed in a closed system; there is a general increase over grade levels in using a uniform particle distribution. A significant finding from use of this item is that a static particle picture remains with students through their levels of instruction. The students' belief of static particles even affects the responses to item 3, because very few students (< 25%) attribute decreased motion with cooling. When students were prompted with item 4, liquefaction is viewed as a change in particle density, students view particles collecting at the bottom of the container. Even before students are

taught particle concepts formally, they have an intuitive notion that liquefaction involves the coming together of particles. A final surprising outcome of this study is an outcome of item 5; there is empty space between particles in a gas. 60% of the subjects beyond junior high school do not picture empty space between particles in a gas. This reinforces the belief by researchers that students have internalized the continuous model and are not willing to relinquish it easily in favor of a particulate model. The authors' overall assessment of their findings is that the numbers of misconceptions do seem to diminish as the level of education increases, however, misconceptions are still frequent in university level students. The implications of the authors' findings are that "writers should explicitly take into account the relative difficulty of various aspects of a model..." They might have include educators in this quote, considering it is the educators' task to relay and relate proper models in scientifically bound contexts. This study highlights the fact that conceptual change should not be expected unless the proper connections are made to the four condition of the conceptual change model. Unless new concepts are placed in terms of appearing "intelligible" and "plausible" to the student, old conceptions based on individual learning will not be exchanged for those shared by the scientific community.

Students' understanding and conceptions associated with PNM is recognized to increase in sophistication as students get older and progress through formal education. This is viewed as beneficial as it is possible to determine the extent to which the conceptions of PNM discovered in lower level students change throughout chemistry courses leading up to the level accomplished by graduate students. It should also be possible to determine if there is a correlation of conceptual meaning among the different age groups by comparing the conceptions demonstrated in the existing literature with those discovered in the current study. Ben-Zvi et al. [49], in describing their study's population of high school students, states that "Micro level explanations are important for understanding chemistry in general and daily occurrences in particular. Although these students who will continue to study chemistry in the university will be helped to strengthen their micro level thinking, the majority of the students will

cease their science studies after high school…" This statement exemplifies the assumption that is often made, chemistry students will form a correct concept of PNM throughout their undergraduate experience. There are several reasons why there is a need to investigate physical chemistry students' conceptions of PNM. First, by looking at conceptions used by physical chemistry students who are at the end of their undergraduate careers is a good indication of whether PNM concepts are strengthened at the university level. Second, physical chemistry students' conceptions of PNM are under-represented in the literature. It is the hope of the author that by investigating the PNM conceptions of this population, the gap that exists between introductory level and graduate level college students can be filled.

Students' PNM Misconceptions-
Partial Fulfillment of Conceptual Change

College students often view chemistry as one of those courses they must "get through" in order to graduate. Step into any lecture hall where a chemistry lesson is about to take place and you are likely to overhear students complaining of symptoms of frustration caused by the feeling of not fully understanding the perceived complex nature of the various concepts covered by the instructor. PNM is one such concept that students have difficulty with and what concepts students form for PNM is of great concern for chemistry instruction in general because it affects the understanding of many chemistry topics. Chemistry students are faced with PNM based phenomena during the study of topics such as gas and liquid diffusion, macro- and nanoscopic changes associated with changes of state (solid, liquid, gas), and the physical interactions of solids, liquids, and gases with various forms of energy (heat, light, etc.) while in the process of forming scientific knowledge throughout their academic careers.

As has been shown through the previous discussion, the concepts that are taught are rarely received by the learner with the educator's intended meaning fully intact. Instead, meanings for concepts are constructed by the learner and influenced by individual and social experiences and everyday real-world knowledge. Formation of PNM conceptions as they relate to chemistry is just one example of how students go about trying to make sense of scientific phenomena they experience in the formal academic setting [37]. There are many parallels that can be drawn between the perceived trouble students have in forming correct PNM conceptions and other concepts important to scientific understanding. One recurrent theme is that students tend to have in place preconceptions about the nature of most scientific topics.

According to Tsai's summation [67], student's existing conceptions serve an important role in the way new information, as knowledge, is formed in the mind of the learner. Tsai also echoes the belief that many of the preconceptions brought into the formal instruction process are resistant to change because they are accumulated over a lifetime. New knowledge is formed as a function of an individual's personal and social experiences, which plays a role in both an individual's preconceptions as well as what meaning is assigned to new information presented throughout the learning process.

So far, students' developing conceptions of PNM at various age levels have been discussed. However, many researchers do not focus their attentions on discovering students' conceptions of PNM for the purpose of facilitating the conditions for conceptual change. Rather, most research is interested in describing students' conceptions that are misaligned with popular scientific belief. This method of discovering divergent science conceptions is a common practice [3, 8, 9, 14, 16-18, 26, 27, 35, 62, 64, 68-83], and is usually accomplished with the hopes of being able to correct those conceptions that students have that are viewed as invalid or providing incorrect explanations of scientific phenomena. The results of

typical research provides educators with undesirable concepts identified in a given student population, however, lists of misconceptions do not provide all the information about what students know. In order to affect conceptual change, not only the "wrong" conceptions need to be identified, the existing conceptions should be identified and utilized in order to exchange existing conceptions for those conceptions that contain correct scientific knowledge [84]. To evaluate the assumption that chemistry students' conceptions of PNM change with academic experience, it is first necessary to review the aspects of PNM conceptions that are identified through misconceptions research.

Alan Griffiths and Kirk Preston [18] conducted one such investigation in order to identify prevalent misconceptions among 12th graders. The authors define misconception as "any conceptual idea whose meaning deviates from the one commonly accepted by scientific consensus." The main stream of thought is that if misconceptions can be identified, curriculum material and techniques can be introduced to realign a student's concept with what is held as scientifically correct. Through the Griffiths et al research, they hoped to answer the following questions: (1) Which concepts relating to molecules and atoms are misunderstood and therefore limit students' understanding of the topics, and (2) How do misconceptions differ among students who differ in academic ability and level of participation in science? The authors used 30 semi-structured interview, with questions generated from a pilot study involving six students. Two groups of questions were asked, one set relating to concepts of atoms and another set focused on concepts of molecules. The study population was drawn from grade 12 and included 30 students, 18 males and 12 females at the ages of 16-18. The students were divided into three categories, 10 students per category, according to their area of study and academic averages. The three categories were academic science, academic-nonscience, and nonacademic-nonscience. Academic subjects were reported of having at least a 75% average, while science subjects had completed or were attempting to complete three high school science courses. The authors state "the purpose of selecting a sample in

this way was to provide a cross section of ability and type of course, and to eliminate bias emanating from individual teachers and schools". In total, the authors discovered 52 separate misconceptions. For the purposes of this paper, only misconceptions that are more likely to be present in advanced chemistry students will be discussed. The first group of questions was generated to elicit students' concepts of structures. The students were asked to draw a nanoscopic representation of a water molecule. From this the authors discovered several misconceptions including: students believe that molecules have no definite shape, a water molecule is spherical with particles spread throughout, and that a molecule of water is composed of two or more solid spheres. What the authors found interesting is that most of the subjects holding these misconceptions were from the academic-science group, which they say indicates that the misconceptions arose from "aspects of the academic instructional treatment." The next group of questions was generated to expose students' understanding of the composition of molecules. Students were asked what water is made of, how many atoms are found in a molecule of water, and how the molecule would be different depending on the phase it was in. Almost half of the subjects said that water molecules contain components other than oxygen and hydrogen. Approximately one-third of the students believed that all molecules of water are not composed of the same atoms. Students also had trouble identifying the correct number of atoms in a molecule of water, with one-third suggesting that there would be thousands of atoms in a water molecule. This type of answer was also found when students considered the phase that the water molecule was in, suggesting that a solid water molecule contained more atoms than if the molecule was in liquid or gas form. The third set of questions focused on students' conceptions of sizes of molecules, again using a water molecule as an example of something macro-sized. The authors state that macro-sized could be compared to the size of a germ, point of a pencil, or like a dot. The opposite thought was also present, where students believed that a water molecule would be the smallest indivisible entity. Over 75% of the students believed that the size of the molecule was dependent on the phase the molecule was in. 40% of the

students in this study believed that solid water molecules were the largest and accounted for properties that could be observed, i.e. expanding ice. A fourth group of questions dealt with what students believed about the shapes of molecules. The most prominent misconception found here was that students believe that the shape is also dependent on the phase of the molecule, mainly shape being affected by temperature. These findings correlated with findings from groups of questions directed at the weight of molecules (group 5) and how molecules bond (group 6). A majority of the students believe that weight of a molecule is also dependent of the temperature of the molecule (why ice floats) and water molecules form intermolecular bonds differently at different temperatures, explaining the different properties of ice, liquid water, and steam. The same groups of questions were repeated, instead of asking about molecules, the authors ask the students to describe atoms. From these groups of questions many similar misconceptions were discovered. Students believe that the size of an atom is much larger that it really is, and can be directly observed. Interestingly enough, students believe that as atoms are heated, they can expand. Unlike students' misconceptions about how the same molecule's weight can vary, students have the correct belief that different elements do have different weights. Only one misconception was found and that was that seven students said that all atoms weighed the same. More than one-half of the students believed the atoms are alive, which the authors state is consistent with a belief that all of nature is alive and sensitive.

The authors give a primary reason for these types of misconceptions existing among high school students: educators promote scientific beliefs that have been discarded by scientists. "These include the belief that macroscopic shapes reflect molecular shapes, that matter is continuous and that all of nature is alive and sensitive", in the context that liquids and solids reflect the shape of their container. The reason could also be that educators are not aware of how students' conceptions are shared through social interactions and that students participate in shared meanings of natural phenomena.

Haidar and Abraham's [58] study showed how conceptions of PNM are viewed through misconceptions by demonstrating chemistry students' applied and theoretical knowledge concerning the particulate nature of matter. They based their research on the wide variety of previous work and conclusions drawn on that work. They reflect some of the findings of other studies of the time which include that formal reasoning ability is associated with greater understanding of atomic and molecular concepts [85], students resist using atoms and molecules in explaining chemical phenomena [5], and students hold many alternative conceptions concerning atomic and molecular models, many of which result from trying to make sense of their world and are resistant to change despite formal instruction. For example, Marin and Benarroch [66] review empirical work conducted by Piaget and Inhelder, where Piaget and Inhelder were interested in determining at what age personal conceptions of PNM first appear. They used sugar dissolving in water, a kernel of corn expanding when heated, and rising mercury in a thermometer as examples of phenomena that most subjects have personal experience with but do not typically think about interactions on a nanoscopic level (in terms of atoms and molecules). This work is essential to the present argument because it shows how personal experiences affect meanings of macroscopic phenomena without influencing or even establishing concepts at the nanoscopic level. Instead, macro-level conceptions are used as the body of common knowledge when students are asked to think about atoms and molecules.

Novik and Nussbaum [50] also provide pivotal evidence of what can be expected with respect to changes in conceptions associated with misconceptions at the different age groups found in an average college student population.

The misconceptions identified in 14 studies (see Figure Six, p. 129) investigating PNM misconceptions [3, 7, 10, 17-19, 34, 49, 50, 55, 58, 79, 81, 86] show that students at different age and ability levels do not gain a firm grasp on PNM. However, advanced-level college chemistry students is not represented by the literature.

PURPOSE AND OBJECTIVES

It is thought that this difficulty with understanding PNM carries over to other chemistry concepts that are based on the behavior of particles. Students who do not make conceptual sense of PNM will have difficulty understanding other major concepts in introductory chemistry and later in advanced chemistry courses, however, the assumption exists that students who attend university will have their PNM conceptions strengthened [49].

This leads to a general question for this study: Are there meaningful conceptual changes that take place in a student's understanding of basic chemistry concepts throughout more complex level of study? If so, are there situations that might lead (cause) students to rely on their own conceptions of chemistry rather than relying on what is assumed they have learned through formal instruction? For this study, it is thought that students' PNM conceptions might be discovered if they are asked to explain a phenomenon that is unfamiliar to them, in this case heat conduction. The suggestion is made that this approach should be possible: students rely on established scientific concepts for certain situations and tend to rely on their individually formed concepts when presented a situation that extends beyond their scientific and common sense understanding of an event. One of the suggested primary reasons for this occurring is if students are not allowed to reflect on the knowledge they have stored in long-term memory representing meaningful learning, previously established concepts will remain and new information is formed along side and independent of the prior conceptions and exists as a separate unit of knowledge [87]. Students will use the new information only when ask to use it within the context it was learned. As new or unfamiliar situations are approached, the students engage in sense

making activities that rely on guidance provided by the deeply established body of common sense knowledge rather than the superficial new information.

It is not the focus of this study to discover new misconceptions or the nature of misconceptions related to the particulate nature of matter and heat conduction because the description of misconceptions is only part of a solution in terms of conceptual change. As well, the area of students' misconceptions relating to the particulate nature of matter are well documented. This study does set out to more fully describe those particulate concepts held by upper-level chemistry students as a check against the assumptions made: students gain correct particulate concepts toward the end of their academic career and are able to utilize the concepts to describe scientific phenomena. Much less work has been accomplished in regards to heat and thermal misconceptions. Fewer misconceptions are identified in the area of thermal phenomena [4, 11, 61, 69, 70, 74, 75, 81, 88-97], and most misconceptions that have been identified are described at the macroscopic level. An explanation for this might be because one does not have to think about atomic or molecular interaction in order think about or describe thermal concepts. As an example, Lewis and Linn [90] reported two misconceptions students tend to have concerning the topic of heat and temperature. Lewis and Linn found that students tend to believe heat and temperature are the same and the authors also found a prevalent misconception of what types of material are conductors versus those that are insulators, i.e. what makes a better conductor, insulator, etc.

A recent paper by Yeo and Zadnik [88] identifies some of the major thermal misconceptions, providing 4 categories and 35 subcategories. The authors provide a review of existing literature dealing with various levels of students' conceptions of heat, temperature, how heat transfers, and how a student views thermal properties of material. The primary focus of their work was to develop a written test on thermal physics concepts to use as an instrument to detect common misconceptions found in student populations. The results provided by Yeo and Zadnik does suggest that most thermal misconceptions are at the

macroscopic level, and therefore getting students to describe heat transfer in particulate terms is a novel approach toward obtaining their particulate views. The connection between the nanoscopic nature of PNM and macroscopic nature of thermal conductivity is that the majority of the misconceptions in both areas seem to be primarily biased based on personal experiences of the subjects. Many studies have shown that, even if instruction provides a more consistent way of dealing with these concepts, students will continue to rely on "real world" analogies versus using scientific concepts promoted by instruction [4, 28, 37, 58, 73, 74, 88, 90, 98-103]. Asking students to explain heat transfer through various materials on the atomic/ molecular level forces them to rely on their concepts of how atoms and molecules relate to one another. The fact that their attention is directed to the difficult problem of explaining heat transfer, takes their focus off atoms and molecules, and allows their functional concepts of PNM to emerge from their existing knowledge that represents their meaningful (i.e. true) learning. For this study, it is hypothesized that extant conceptions based on personal experiences concerning the nature and interaction of matter makes understanding more complex concepts such as thermal conductivity of matter at the nanoscopic level much more difficult. It is the author's hope to provide the missing description of PNM conceptions that exist for advanced-level chemistry and show how students come to apply these conceptions when faced with unfamiliar phenomena, using heat transfer through various materials (thermodynamics) as an example.

Research Questions:

There are three main research questions that guides the development and execution of the current research:

1) What are the concepts of PNM physical chemistry students use when describing the process of heat transfer on an atomic level?
1) How do these concepts compare to those present among introductory level students?

1) How do these concepts compare to concepts documented in existing literature?

The answers to these questions can be used to inform educators as to the extent and effectiveness of relayed meaning during the education process. As well, information that is provided can be used by educational researchers wanting to explore ways of affecting the education process through the conceptual change model.

PROCEDURES

Research Method

The study is interpretive qualitative and hypothesis building (exploratory) in nature and will involve three separate populations at the university level. Qualitative methodology is a research methodology used to provide findings through non-statistical measures. According to Strauss and Corbin [104], qualitative methods can be used when " intricate details about phenomena such as feelings, thought processes, and emotions that are difficult to extract or learn about through more conventional research methods". It is the intricacies associated with students' conceptions that led to the employment of the qualitative method. As previously discussed, students' concepts are influenced by many factors, not just what they are presented in the classroom. By taking a qualitative approach, it is thought that much more can be learned about the *way* students think about atoms and molecules, not just *what* the students think. This study was accomplished using multiple phases of investigation. Each phase will be discussed independently as they relate to the progress and implication to the overall investigation.

Sample Description:

A physical chemistry student is defined for the purpose of this study as a student who has had or is currently enrolled in the thermodynamics portion of what is typically a two or three-semester physical chemistry curriculum at the undergraduate level. This level of student is attractive for two reasons. First, a thermodynamics course is considered to be upper-level, meaning students have

usually attained a junior or senior-level status. The sample for this study was mostly seniors (over 75%) and the majors were evenly split between chemistry and chemical engineering. Students at this level should be able to demonstrate an advanced level of sophistication in concepts typically associated with chemistry. Students at this level of chemistry study have generally received instruction on PNM concepts and have had many opportunities to form and apply their conceptions of PNM. Through an investigation of advanced level chemistry students, data can be gathered to support or discredit the assumptions that are made about what students actually know about PNM. The second attractive feature for this population of students is that this population is not well represented in the literature, yet this is the student population that will most likely go on to advanced levels of chemistry study and research. Only one study involves the conceptual understanding of physical chemistry students [105], and is mainly on the topic of kinetic equilibrium found within thermodynamic systems and has very little in common with this study other than the participants.

The second population for sampling is students who have taken or are currently enrolled in chemistry courses considered to be introductory in nature, namely, the first semester of a what is typically a two semester general chemistry course at most four-year institutions. At present, due to time constraints, only four-year institutions are considered for this phase of study. It is necessary to collect information about how introductory-level students use PNM conceptions when explaining heat conduction. This information, combined with those concepts described in the existing literature, will provide a baseline for comparison for those conceptions of the upper-level physical chemistry students. This is a necessary step because it is not possible to know what those particular upper-level students' conceptions of PNM were when they were at the introductory level. Therefore, the closest representation is to know at least how a sample of students at the introductory level currently utilize PNM concepts when attempting to explain heat conduction.

The third population consists of educators who teach thermodynamics and transport processes. This population is used to examine professionals' ideas

about what concepts of PNM students at the various levels of academic achievement should hold or are believed to hold (the assumption discussed earlier). This population is also used to inform the study as to what is scientifically accepted and practiced concerning PNM and will constitute an "expert" concept picture. Several of the articles mentioned above help to define what is presently accepted as scientifically acceptable. However, this information will be taken together with the expert opinions to form a baseline of what concepts can be expected to be demonstrated by subjects. Again, the main focus of this investigation is to collect conceptual meanings rather than judge those concepts as scientifically acceptable. It is possible that the current study could be extended to determine how student's conceptions align with scientifically accepted knowledge. All participants are asked to participate on a voluntary basis and were sampled from several four-year institutions.

Data Collection

The data was generated from two data sources, both lending to a qualitative approach. First, an open-ended survey was completed by all participating students with questions about the nanoscopic (atomic or molecular) aspects of heat transferring through a solid. As discussed earlier, it should be possible to get to students' conceptions of PNM by asking them to respond to questions about phenomena that exceed their understanding. Semi-structured interviews with upper-level students who agree to participate are used to further elucidate their concepts as well as to clarify and verify meanings of conceptions these students demonstrated during the open-ended question portion of the study. A protocol for this study was submitted to the Institutional Review Board (IRB) for consideration and was approved.

RESULTS

Intermediate data

Phase One: Formulation of Open-Ended Questions Instrument

A pilot study of 65 introductory level students was conducted in which subjects responded to two open-ended questions after they observed a demonstration of heat conduction through various materials. The demonstration is based on an experiment described in the lab manual *Teaching General Chemistry: A Material Science Companion* [106]. Small pieces of pasta (elbow macaroni) are attached to the ends of rods of various materials using butter. The materials used were copper, zinc, aluminum, brass, nylon, and glass. The rods used were 153 millimeters long and 6 millimeters in diameter. All of the rods were placed into a styrofoam container and then boiling water is poured in until the cup is full. The students then observed how long it took for the butter at the end of the rods to melt by noting the time at which each piece of pasta fell. From this point forward this particular laboratory will be referred to as the "Pasta Lab". The Pasta Lab is typically used when students are studying thermal conductivity to emphasize the fact that different materials have different thermal conductivity coefficients and therefore conduct heat along their lengths at different rates. For an example of how thermal conductivities are typically used to show the flow of energy through a material, please see Figure Seven. The concept of thermal conductivity that results from this lab is typically a macroscopic level conception. Students do not typically learn what atomic-molecular properties of a material cause it to have the thermal conductivity coefficients that it does and therefore students are unfamiliar with trying to explain this concept at the particulate level. After the pasta falls from the rods (or not in the case of nylon and glass because they have tremendously low thermal conductivity coefficients and the butter does not melt),

students were asked to respond to two written questions. The questions were, "How did the heat get to the butter to melt it so that the pasta could fall?" and "Why did the pasta fall for some of the rods earlier than others?" The students were then asked to answer the two questions again after they were instructed to use the concept of atoms and molecules to answer the first question and instructed to think about what makes different materials different on a nanoscopic scale and use these differences to answer the second question. The difference in student understanding between the two sets of questions can be seen as the difference between something concrete, the empirical nature of the thermal conductivity coefficients, and abstract thought about how atoms interact to transfer heat energy from one end of a rod to the other.

The resulting data was analyzed by content analysis [107], where similar particulate concepts contained in students' responses were grouped together. It was the intent to use the resulting data to formulate open-ended questions to be incorporated into the main study.

A common response to question one was that the heat got to the pasta by heat transferring from the water to the rods and then to the butter. There were several students who believed that steam played a bigger part in melting the butter. Through this method, the students believed heat transfers to the butter by the shortest route, hot water heats the air surrounding the butter, and in turn the hot air warmed the butter, melts it and released the pasta. The most common response given by students is exemplified by student 05-DE-TH:

> "The heat got to the butter through the rods. The rods are made of atoms and transfer heat energy throughout the rod; therefore the top of the rods became hot, and melted the butter. Metals are excellent sources of carrying energy (heat, electricity, etc.) because of the atoms that make them. Heat causes the atoms to move, or spread out "

The majority of students gave this type of response, because metal rods are used and are familiar heat conductors, the rods conducted the heat from the water and transferred the heat to the butter, causing it to transform from a solid to a liquid. Students responding in a different manner tend to describe the solid butter holding the pasta as having potential energy and then kinetic energy is transferred from the boiling water through the rods but not to the butter. As seen in the following students' responses, it is the fact that the rods become hot from the energy transfer that is directly responsible for the phase change of the butter rather than energy being transferred to the butter.

23-JU-KE

> "The different metal sticks are conductors, and they were heated up when the boiling water was added to the cup. When the sticks were warm enough they melted the butter, causing the pasta to fall."

02-JO-AL

> "The heat from the water caused the rod to heat up. The atoms are thus moving at a faster rate now. Well the heat from the rod has caused the butter to become hot as well. The butter was in a solid form to begin with. The atoms, when heated, began to move faster thus moving the butter into a liquid stage. The pasta was being held on by the solid butter, but cannot stay on when the butter is melted."

From these responses, we see a particulate explanation for the first question: rods are made of atoms and the atoms speed up when exposed to the rapidly moving water molecules. Some students used a combination of macroscopic and nanoscopic concepts to explain how this energy transfer works, invoking not only atomic collisions but also friction to explain the process by which heat

transfers through the length of the rod. The energy contained in the moving atoms is then further transferred to the butter, causing it to gain energy and melt:

30-DC-RO

> "The heat from the water caused the particles inside the rods to speed up. The speeding up of particles/ atoms develops heat, from the atoms hitting each other. So, the heating of the rods caused the butter to then melt and the pasta to fall off."

What is interesting is that students seem to be applying to these solid rods what they learn about how energy is transferred through atoms or molecules of an ideal gas, more formally known as the kinetic molecular theory.
The fact that students had not been exposed to the atomic and molecular interaction for the process of heat conduction is apparent in the responses to second question. A few student responses relate density of a material to the ability to conduct heat. Although the majority did not use the term density, most expressed ideas commonly associated with density. The interesting finding for the second question is that about half of the students stated that heavier metals were harder to heat up and therefore took longer to melt the butter. Other students, although fewer in number, stated exactly the opposite, that lighter metals melted the butter slower than heavy metals. Those that expressed the belief that heavier metals are harder to heat can be seen as recalling and applying a macro level concept, momentum, as it takes heavier objects more energy to overcome inertia. Another popular response to this question is that the better conductors melt the butter faster without supplying a reason why the materials might be better on an atomic scale. The reason this might be is most students have everyday experience with the types of materials that make better electrical conductors, without having experience of particulate theories. In the sample only two students offered an explanation of what a better conductor was,

relating to existence of empty orbitals found in the atoms involved, which sounds more like electrical conduction than heat conduction.

The responses of the students for the pilot study were used to formulate the following five open-ended questions designed to target subjects conceptions of PNM for the present study. Each question was created to access those conceptions demonstrated by the subjects of the pilot study for each of the planned sample populations.

- Why did the butter melt after the hot water was poured into the cup?
- What is the path heat travels in getting from the hot water to the butter?
- All of the materials in this experiment (and everywhere) are made of atoms. Describe what you think is happening on the atomic level as the heat travels from the hot water to the butter.
- Why did the pasta fall for some of the rods earlier than for other rods? (Please explain this both in general terms and then at the atomic level as you understand it.) Include a list of the materials in the order that the pasta fell from fastest to slowest.
- Would the same rods that seem to be good conductors of heat also be good conductors of electricity? Why or why not?

Phase Two: Introductory-level Students' Conceptions of PNM

The five open-ended questions instrument (OEQI) that resulted from the pilot study was answered by two sections (n=41) of introductory level chemistry students (non-chemistry majors) from a mid-western college during the fall semester 2001. Although the sample was convenient as opposed to randomly selected, the students do fit into the study's sampling frame. It was agreed that the OEQI would be incorporated into the normal graded coursework for all students and only those responses for students that signed an informed consent form would be forwarded and used as data. The students gave responses for the OEQI during the lab period when the students performed the Pasta Lab while

studying the topic of thermal conductivity. Once the responses were received, they were analyzed for particulate concept content aided by qualitative data analysis software (HYPERRESEARCH 2.3) using an emerging (open) coding scheme [104]. The purpose of conducting qualitative analysis at this point is to look for patterns or common themes within the concepts. In other words, because the interest is in all conceptions of PNM, as new or different conceptions emerged from the data, a code was created for that concept. Table One shows the resulting codes for the concepts that emerged from the data. Table Two provides definitions for the codes found in Table One.

Table One: Introductory-level PNM concepts for phase 1 using original coding scheme.

Intro level														
n=41	Code	Freq		Code	Freq		Code	Freq		Code	Freq		Code	Freq
Q1			Q2			Q3			Q4			Q5		
	C22	1		C5	1		C4	1		C6	1		C16	1
	C25	11		C28	1		C23	1		C25	1		C18	1
	C26	29		C2	2		C10	1		C1	3		C20	1
				C26	4		C28	1		C12	13		C7	3
				C29	35		C9	1		C13	18		C15	12
							C2	1		C11	33		C19	13
							C21	2						
							C1	2						
							C3	2						
							C24	2						
							C8	3						
							C17	3						
							C27	3						
							C6	4						
							C20	14						
							C5	33						

Table Two: Emergent code definitions introductory level PNM phase 1

C1	Student indicates that heated or excited energy state atom travels through the rod and delivers heat or energy to the butter to cause it to melt.
C2	Student describes the heat being passed from atom to atom.
C3	Student indicates the atom is a single unit versus those who treat the electrons separate from the rest of the atom.
C4	Student indicates that as atoms are moving they create energy.
C5	Student indicates the motion of the atom, whether described as vibrational or excited, increases because heat is added to the system.
C6	Student uses term atomic level in a context that means the same as "excited" or moving rapidly.
C7	Student only provides an explanation for the phenomenon based on personal experience and examples.
C8	Higher energy state causes bonds in either the material or target to break.
C9	Student describes the bond being weakened as a result of an increase in motion.
C10	Student believes that heat is a result of a chemical reaction between the water and metal.
C11	Student relates different rate of falling noodles to the difference in thermal conductivity etc.
C12	Student describes the reason for the differences in rate based on macroscopic reasons.
C13	Student describes the reason for the differences in rate based on nanoscopic reasons.
C14	Student described different rates in terms of atomic interactions.
C15	Describes specific atomic property.
C16	Specifically uses term density as reason for differences in materials ability to conduct.
C17	Describes the heat energy absorbed and released as being equal.
C18	Student uses terms to indicate that although both forms of energy, do not conduct in the same way.
C19	Terms describe both heat and electricity as forms of energy which should behave the same.
C20	Use of heat and temperature interchangeable.
C21	Indicates electron involvement.
C22	Heat transferred from water to butter, does not discuss the transfer through the rod.
C23	Student describes how heat increases atomic interactions.
C24	Student describes heat causing increased motion and increased motion in turn causes increased heat, maybe thinking in terms of physical contact (friction?)
C25	Student describes the heat being transferred into the rod and the hot rod melts the butter, instead of energy transfer.
C26	Student describes heat being transferred through the rod.
C27	Student used specific term to describe the motion, beyond general terms like "excited".
C28	Student describes heat from steam responsible for melting the butter.
C29	Student describes path without describing the nanoscopic interactions.

Discussion of Introductory-level Students' Phase Two Responses

In order to answer the main research questions, it is necessary to concentrate on the main concepts identified from the data using qualitative analysis. It was anticipated that all students who participated in this study would not know the particulate mechanism responsible for heat transfer. The following response from a theoretical physical chemist was used as the key to evaluate student OEQI responses:

> " The H_2O is at a higher temperature than the rods/butter/noodle. Heat statistically is overwhelmingly likely to travel from hot to cold. Molecular vibrations and librations in the H_2O excite vibrations (and electrons) in the metal and these vibrations in the metal further excite vibrations along the length of the rod resulting in heat transfer. The vibrations in the metal then transfer energy to the butter in an analogous fashion."

From analysis of responses to the first question, two major themes are apparent. First, students describe a process where kinetic energy from the water causes the atoms in the rods to become excited. The increased excitation is seen to cause the atoms to move and collide more. As a result of increased physical interactions, the rods heat up and cause the butter to melt. In these cases it was rare that students described an energy transfer into the butter to cause it to melt, rather it looks as if they have a concept of energy transferring to the rod, making the atoms in the rod interact more which results in the rod becoming hot and it is the fact that the rod has become hot that results in the butter melting. The majority of the responses did indicate that energy was transferred through the rods to the butter, however, very few explained how the heat energy was transferred through the rods on an atomic level in response to the first question, which did not specifically request a particulate explanation. The same macroscopic explanations are seen again in the majority of students for question two. There is current research that suggests that the concepts presented in student answers depend on how the questions are asked. Williamson [108]

showed that if you ask students questions that contain particulate terms, the answers they generate will typically follow suit. Questions one and two do not contain particulate terms, so it is expected that answers will remain at the macroscopic level in detail. Question three asks in particulate terms and as a result, it is apparent that the numbers of particulate answers increased in both number and variability. The main theme found in question three is that although students describe atoms as becoming excited or moving more as a result of the introduced heat, they do not tend to provide a description of any atomic or molecular interactions. A few examples of this follow:

Student Xpe819 states:
"As the heat travels through the rod to the butter is excites the atoms of the butter, causing it to melt."

Bes715:
"On the atomic level, as the heat travels from the hot water to the butter, the atoms are probably moving faster, thus making the rods heat up."

Nmq650:
" As the heat travels from the hot water through the butter the molecules or atoms are vibrating. Then the movement of the vibrations cause the movement of heat."

As can be seen by the last response, some of the concepts have hints of atomic interactions but the interactions are not described fully. The responses for question four are interesting because the question asked for a nanoscopic description and the majority of responses indicated that the reason some rods fall faster than others is because they have better thermal conductivity coefficients. This again reemphasizes that this was a thermal conductivity lab and that a particulate description is not the focus. The major emergent concept for question five is that electricity and heat are both forms of energy and therefore should

transfer through a material either by the same mechanism or at the same rate. The typical student response for this question may be the results of everyday sense making playing a part in the concept of electricity transfer. Students come to the classroom with common knowledge of electricity; it is part of their everyday life. They learn that electricity is energy, after all, we have to keep turning off the lights to keep the energy bill low. They seem not to be thinking about electricity on a particulate level much like that found with heat transfer. The combined data from the OEQI suggest that students at the introductory level have a difficult time thinking about heat conduction on the particulate level. This statement exists on the tip of a double-edged sword; students at the introductory college level are not expected to have fully functioning PNM concepts. At the same time however, secondary level students are usually exposed to PNM concepts and literature says [10, 11, 14, 60, 109] that they should be able to use those concepts to at least portray a general understanding.

Phase Two: Physical Chemistry Students' Conceptions of PNM

The data collected on introductory level students provided a baseline for what that particular level of student knows and how they go about thinking of particulate phenomena. It is assumed that by the time a student has been through several chemistry courses that more robust PNM concepts will exist in the knowledge framework of the student. In order to see if PNM concepts changed with academic experience, a lecture class of physical chemistry students at the author's university was given the OEQI at the end of the fall semester, 2001, when most of the planned thermodynamic topics had been covered. The OEQI was again incorporated into the students' coursework, everyone that completed the questions and turned it in received extra credit toward an exam grade. Only those students that volunteered to participate in the study (n=27) had their responses analyzed. Unlike the introductory students, these students observed the Pasta Lab as a demonstration and did not perform it themselves. The students were split into groups and rods were passed out for

the groups of students to examine to alleviate any problems cased by lack of familiarity with the materials used in the demonstration. After the demonstration, the OEQI was completed before any discussions among the students could take place. The data was analyzed using an emergent scheme as before. As concepts emerged, they were given a code. The results are found in Table Three and definitions of the codes are found in Table Four.

Table Three: PChem PNM concepts phase 1 using derived coding scheme

Pchem														
Final n=26	Code	Freq		Code	Freq		Code	Freq		Code	Freq		Code	Freq
Q1			Q2			Q3			Q4			Q5		
	D8	1		D14	1		D2	1		D6	1		D18	5
	D16	2		D16	1		D6	1		D13	1		D10	11
	D9	3		D17	1		D16	1		D15	1			
	D19	6		D19	8		D20	3		D2	2			
	D17	18		D9	17		D1	5		D7	2			
							D19	5		D4	3			
							D8	6		D5	4			
							D11	10		D12	6			
							D9	15		D3	13			

Table Four: Emergent code definitions phase 1

D1	Students use the term vibrational or vibrating in describing the atomic or electronic motion
D2	Student uses terms to relate that a specific atom or a specific type of atom is responsible for carrying the heat to the butter.
D3	Students described the reason for the rate at which noodles fell was directly dependent on either the specific heat, heat capacity, or thermal conductivity values.
D4	Students used terms to describe the conductivity rates as dependent on how easily atoms could become excited.
D5	Student uses terms to describe characteristics of electrons and how the electrons are involved in transfer of heat.
D6	Student describes how density inhibits transfer of heat, whether because of tighter bonds between atoms or less room for atoms or electrons to move.
D7	Student describes how more room between atoms would relate to electrons or atoms themselves to "roam" more freely, lessening the inhibition of heat transfer.
D8	Student uses terms interchangeably, appears that heat and kinetic energy are the same.
D9	Student relates physical contact of either atomic or electronic components as mechanism for heat transfer.
D10	Student relates physical contact of electronic components specifically as mechanism for heat transfer.
D11	Student describes increased motion of atoms or electrons as a direct result of heating the system.
D12	Student describes how less room between atoms would relate to electrons or atoms themselves to be more likely to have physical interaction with neighboring atoms or electrons to facilitate heat transfer.
D13	Student uses terms to indicate that materials that have lower heat capacities will transfer heat faster.
D14	Student describes atomic motion having physical effect on the noodle, i.e. because the atoms were vibrating, they vibrated the noodle off of the rod.
D15	Student uses terms related to pure substance or compounds to explain differences in conductivity.
D16	Students used terms to describe the rod accepting heat from water and melts butter because the rod is hot, not that there was energy transferred into the butter to cause the noodle to fall.
D17	Students used terms to describe the rod accepting heat from water and then transferring the heat or energy to the butter which melts butter to cause the noodle to fall.
D18	Student explains the difference of how heat and electricity are conducted.
D19	Student explains that heat is conducted because all portions of a system want to be in equilibrium.
D20	Student who describe energy in terms of temperature or used temperature and heat interchangeably.

Discussion of Physical Chemistry Students' Phase Two Responses

For question one, approximately half of the students answered at the macroscopic level by describing how the heat is transferred to the rods and then to the butter to cause it to melt. The main difference between this sample and the sample of introductory level responses is that a third of these upper level students provided a reason for heat transfer: the system wanting to reach equilibrium. However, again there was a lack of particulate responses to this question which did not specifically request a particulate response, indicating that these students as well do not immediately think of heat transfer in particulate terms. There were fewer responses in the advanced level sample that reflected the common introductory level response: the butter melted simply because the rod got hot. This may indicate that even though the advanced level students did not describe atomic or molecular interactions, they may at least have a familiarity with the terminology associated with nanoscopic interactions which allows them to answer the question differently than the introductory level student.

Students described the pathway for question two much like the introductory level students, however, they tended to incorporate more particulate terminology to describe the way the heat traveled from the water to the rod and then to the butter.

> Zqs432
> "From the water up the rod to the end with the butter. The heat increases the energy of the atoms submerged in the water, this energy is moved up through the rod by intermolecular interactions."

> Tnh713
> "Heat travels from the hot water molecules to the molecules of the rod which are actually in contact with the water first. The 0th law the heat permeates up the length of rod, evenly distributing the extra heat obtained from the water. At the top the butter is cooler

than the rod so the extra energy flows into the butter increasing its temperature and melting it."

Bnm567
"From the bottom of the rod where atoms are excited by hot water to the top of the rod."

As one can see from the examples, even though more particulate terminology is used, there is still not a clear description of the interaction between particles that would account for the heat being transferred.

The responses for question three were not as disparate as those found among the introductory students. In fact, all but a few students shared one of two concepts, which indicates that students may at least assimilate meanings for particulate terminology, even if the conceptual meaning has not been fully accommodated. In other words, it seems as though students are using particulate terms without having the ability to apply particulate concepts. There are more students that describe heat or energy causing the atoms and molecules to increase in motion. As examples:

Tnh713
"Temperature is a measure of heat and heat is a form of energy. Where as work is ordered motion of atoms, heat is the random motion of molecules. As you increase the temperature, you know that there is more heat, and thus more energy. This energy causes the molecules (all of which in the universe are in motion) to increase in speed and move around faster."

UHN654
"When an object is heated its energy is greatly increased and the atoms move around rapidly some of these excited atoms do organized motion or work to heat the rods."

Bnm567

"The atoms at the bottom of the rod are excited and give up energy from the heat that they received from the hot water to the nearby atoms. This way the energy is transferred from one atom to the other until it gets to the butter molecules."

Several students went as far as to describe the motion involved:

Okm654

"The atoms at each material begin to vibrate more (increasing their velocity) As the velocity of atoms increasing, the temperature must be increasing. The velocity of the atoms on the lower part of rod are much higher than the top of the rod until the temperature reaches equilibrium at which the velocity is equal all throughout the rod."

Rby612

"As the heat is transferred to the atoms in the rods from the atoms in the water, the atoms are excited and begin to vibrate more (increase kinetic energy), which excites the atoms next to those atoms and creates a cascade effect throughout the material, heating it. The initial excitement of the rod material is due to collisions by H_2O."

Bnm765

"All of the atoms are heating up. The heat is causing the atoms to get excited. As the heat increases the atoms begin to vibrate more. The temperature will travel through the atoms in the rods causing the particles to vibrate."

Students are again showing that they are thinking about atoms and molecules interacting; however, they are not expressing a description of the interactions using particulate concepts. The second common conception found for this sample was the thought that energy is transferred through the material by atoms physically colliding. As examples:

> Ces574
>
> "Since the atoms are packed close together, as they receive heat (measure of kinetic energy) they collide more and according to 0th law of thermodynamics heat flows to cooler areas so the energy flows up the column by exciting atoms causing them to collide with their neighboring atoms until they reach the butter which melts."
>
> Zdr689
>
> "The kinetic energy of the water atoms is transferred to the atoms of the rods through collisions. This increases the kinetic (temperature) energy of the atoms in the rod. As the atoms in the rod become more excited, they collide with their neighboring metal atoms until the full length of the rod is full of atoms at the higher kinetic energy state. The atoms of the metal that are in contact with the atoms of the butter then collide with the butter atoms and impart kinetic energy to the butter atoms. This increased energy causes on phase change in the butter from solid to liquid."
>
> IJN867
>
> "On the atomic level the atoms of the hot water collide with the atoms in the rod which in turn collide with the atoms in the butter."

The examples presented above represent the application of kinetic molecular theory, even when thinking about atomic interactions within a solid. The responses also include students who describe the heat being transferred through the material via electron excitement or electrons that are now vibrating at an increased rate. This way of thinking about heat was first detected in the pilot study data when it was noticed that many students described the transfer of heat much as they do electricity.

The student responses for question four were very much like the introductory-level students, although more elaborate in the language used, in that they explain why some metals conduct heat faster depends on the materials thermal conductivity coefficients or for several students, the specific heat. It appears that students tend to use specific heat and thermal conductivity in the same way. The main point of this finding is that even at the advanced levels, students may not know what nano-level characteristics cause a material to have the empirically derived thermal coefficient that it does. Students are not expected to know the exact characteristics responsible for thermal conductivity, but the fact that they do not speculate is cause for concern. It may be that students at the advanced level are not making the connection of how nano-level interactions lead to bulk properties of materials.

Responses to question five again reinforce the finding that students liken heat transfer to the way electrons are passed through a metal for electrical conduction. This type of response was given even though the students in this group were provided with a table that showed the thermal conductivities and electrical resistivities for the materials used in the Pasta Lab. The table used was set up to show that there was not a clear relationship between a material's ability to transfer heat and electricity; a material that has a high thermal conductivity does not necessarily have a low electrical resistivity. This gives the impression that students do not have a good concept of how atoms and molecules interact to transfer heat. When a likeness or difference is suggested through the question "are rods that are good conductors of heat also good conductors of electricity," common sense says that metals are good electrical

conductors and metals are good heat conductors, therefore they must pass energy the same way, even though the students had the evidence to support the idea that heat and electrical conduction are different. This shows how students rely on engrained concepts of electrical conduction rather than thinking more deeply about the ways in which heat and electricity might be different.

Interviews as a Method to Evaluate Written Responses

It was after the advanced level student data was analyzed that the apparent need for interviews was fully realized. Interviews were planned from the onset of the study, as using the interview is a widely accepted tool within qualitative methodology for drawing out conceptual meaning. The use of interviews is also important because it allows for triangulation of data [107], e.g., a different way of looking at the same set of concepts. The most common triangulation method is "triangulation of measures" where the researcher takes multiple measures of the same phenomena, for this study in the form of open-ended surveys and interviews. Data generated from the OEQI included student responses that needed further clarification, while others contained concepts that needed further probing. For instance, it was necessary to seek the concepts that exist in students' minds when they use terms such as "atoms collide" or "causes the atoms to vibrate more" ; an interview would give them the opportunity to clarify and explain what they really meant by their responses. It would also allow the students a chance to elaborate on those concepts that they briefly explained on paper.

It was decided that using a semi-structured interview [110] would be the best method for interviewing students about their concepts. Semi-structured interviews are very much like open-ended questions; however, because the researcher and subject are face to face, there is opportunity for immediate follow-up questioning.

In order to prepare for a semi-structured interview, it is essential to formulate a script which describes how the interview might be conducted and serves as a

guide during the interview process. The interview script preparation provides a way for the interviewer to think about how the person being interviewed might respond to the questions and provides prompts to allow the flow of the interview to continue toward a predetermined direction. The script presented in Figure One was developed for use with the physical chemistry students in this study and provides the reasons the questions are used, as well as the guide questions and prompts are for each question.

Figure One: Interview script used for physical chemistry students.

Question one:

Purpose: to break the ice and to get the students thinking about particulate nature of materials.

Guide questions for question one:

What do you think about this student's response?
Do you believe it to be completely correct?
How important is the steam in transferring heat to the butter?
If we were to suspend the rod with the noodle attached on a string above the boiling water, would the steam play a more important role in the process?

Question two:

Purpose: to see if nanoscopic pathways are mentioned.

Guide questions for question two:

Present Q2R1:

Please tell me to what extent you agree or disagree with the response?

If they agree with the statement, point out that the student has indicated that they believe the atoms eventually become closer together, do they still agree?

If disagree, what points do you disagree with, what do you believe to be correct and incorrect about the response?

Figure One (Continued):

The student should point out that the atoms do not get closer together, instead the atom's distance from each other increases.

Do atoms really expand, what do you mean by expand?
If expand is in terms of atoms getting bigger, get a description, possibly on paper.
If expand is in terms of electrons moving to higher orbital, get a description, ditto.

What is meant by "atoms are being heated up?"

Ask at this point, after description of expand ask if this leads to atoms or electrons touching as indicated by student response. If the conversation leads to electron discussion, pull out Q2R2 and present to the student and get an opinion about the content. Statement on card:

Present Q2R3, ask what is meant by "move" in this response. Lead the student through an exploration of the types of motion they associate with this process.
Question three:
Purpose: information about the roll of material structures.
Present Q3R1, Q3R2
Guide questions for question three:

Ask what the differences are between the two, and which they most agree with and why.

Present Q3R3, to see if tautology is recognized. If not ask if the answer is complete, given the question asks for a description at the atomic level.

If the discussion turns toward specific heat, present R4, and ask if it is a true description.
If time permits, pull Q3R4 and ask about the term directly

Question four:

Purpose: get at concepts of atoms vs. electrons

Guide questions for question four:

Present Q4R1 & Q4R2,

Ask what the differences are between the two, what aspects do they most agree with.
If discussion sticks to atoms, then after pull R3 and ask what they think.
If discussion sticks to electrons, pull Q4R3 and ask what they think.

The interview script is based on the use of cards presented to students during the interviews. The individual cards (please see Figures Two-Five, Appendix, p. 127) contained the questions from the OEQI and sample response quotes that reflected the concepts found in advanced level OEQI responses. The quotes contained on the cards were made up of both physical chemistry and introductory-level responses, the majority coming from the physical chemistry students. In other words, the students being interviewed were given responses

that they themselves had provided or statements that reflected the type of responses from the OEQI that they had previously completed. The physical chemistry students' responses that were used on the cards were changed a bit to conceal the fact that they were from the same group of students.

During the interviews, physical chemistry students were asked to provide their opinions as advanced chemistry students regarding the quotes on the cards, which were said to be from introductory-level students. Of the 26 physical chemistry students that answered the OEQI portion of the study, only four volunteered and were interviewed. This allowed the interview protocol to be evaluated regarding its ability to triangulate.

It was noticed that during the interviews, students tended to describe concepts very differently than was found in their written response. Several examples are provided that show that the concepts demonstrated during the OEQI were not the same as the concepts they demonstrated during the interview.

Student BZA234

This student provided interesting responses for the OEQI phase, particularly for questions three and four which suggested that (s)he was thinking about the heat being passed through interactions with neighboring molecules. On one OEQI response, the student states, "The molecules at higher temperature transfer energy through interactions with the molecules next to them…", and again expresses the idea of physical interactions while discussing how density might play a role in determining the speed a material conducts heat. "A major factor is density, this makes the material dense. It also facilitates neighboring molecule's ability to transfer energy through contacting…". However, during the interview, the student was presented with a card (Figure Three, p. 127, Q2R1) that contained a similar concept and the following conversation ensued:

BZA234	I don't know how much chemistry the guy has had but he does have the idea, that it is, you know conductive, you know, one atom heating up the next one, but he doesn't understand the kinematics, like the actual vibrations and the atoms and crystalline structure, the atomic organization, ... he's trying.
I-1	As far as the idea about what do you think about, what he is saying about, the heated atom basically touching a cold atom. I mean in your view, is that possible?
BZA234	Its not touching, its not touching, that is a very common misconception that atoms touch, and I'm sure if you were to point this out to him , he would be like yeah you cant have an atom touching, he knows that the energy orbital, or that is what he means, they're interfering and the entire energy status of this one, which is kind of the expansion property, because if you are pumping up that energy level and it's touching the next one, so I mean that, I mean it's kind of neat, he really didn't mean that probably, but you could assume that. He knows that one is at some level, interacting with the next one...

As one can see by the example, even though a student uses a concept in written responses, it does not indicate that the same concept has the same meaning when it is presented as if it came from an introductory level student. This particular student used the term "contacting" in the written response, however, believes that atoms are not "touching". This student does go on to explain the process of heat transfer through the rods this way:

BZA234	Through vibration. When the water is poured into the top of the thing, you're going to heat up, excite your atoms at the bottom. Heat is measured in vibration of that molecule, and for whatever reason, that's just the way God made them vibrate, and they don't teach you about God in college, and I don't know, we're just in some, cause I'm not going to get any deeper than that, they vibrate, that's how they measure the heat. Now, as they vibrate, the electrons are excited a little bit, they're going to expand a little bit, and then the molecule is going to interact with that, this nucleus is not going to bump into this nucleus, this electron is not going, hope to God, not bump this electron, otherwise maybe we can find some new energy sources, I don't know, but through that physical interaction, every molecule is excited...

Student IJN867:

An example of how concepts are better defined through the use of interview is provided by review of this student's responses. This student stated on the OEQI for question three that "atoms of the hot water collide with the atoms in the rod, which in turn collide with the atoms in the butter". What does a student mean when they use the term collide, do they really see atoms acting on one another in a physical manner, as if they are thinking about an ideal gas?

The topic of atomic interactions was brought up by the investigator and is approached through a discussion of the response R1 for question two (see Figure One), the same response previously discussed by student Bza234

I-1	Okay. Question 2, I'll go ahead and give you a chance to read the question. (Pause)
IJN867	Um, I would agree with that statement
I-1	You said you would?
IJN867	Yea, I would agree with that.
I-1	Okay.
IJN867	The atom is hot and then it starts moving around more and starts bumping into the atoms next to it and then kinetic energy and heat is like moving around and bumping into like … heat went up the rod and melts the butter.
I-1	Now you say they are going to bump, what do you mean when you say bump, when they bump into their neighbors, what do you mean by that?
IJN867	Well the atoms are moving.
I-1	Right.
IJN867	… atoms like sitting there, no motion at all, then they're moving, they're vibrating, so, there are like atoms around it (pause), the heat is going to travel, the energy is going to travel, (student uses fists to represent a hitting action as (s)he describes it verbally)
I-1	Um, do you see it sort of like pool balls maybe, if you had a bunch of pool balls and you take a pool ball and throw it at the rest of them and they actually hit, do you see it as that kind of

IJN867	Yea.
I-1	You see the atoms actually hitting one another and transferring the energy that way.
IJN867	Yea.
I-1	Okay. And you also said something about moving, um when you think about atoms moving, how do you think, how is the atom moving?
IJN867	It's moving electrons, I would say, they atoms within a sphere, so an electron can start going all around the electron cloud ...
I-1	So you see the electrons moving in this whirling kind of
IJN867	Right.
I-1	Everywhere all the time? And what about the nuclear forces on the atom, what do you think is going on there?
IJN867	I'm not sure...

It is easy to see that this student has a mental picture of atoms actually coming in contact with each other. It was also obvious that the student had difficulty thinking about what the atomic interactions might look like if (s)he could really see them.

Other students had an easier time with this mental picture. The following portion of dialog takes place after the student has mentioned that electrons exert forces on each other as a means of transferring heat energy.

I-1	So you see it as, do you see it as an actual force, electron to electron is a force or is it physical interaction? (Hits fists together to describe the interaction)
Zqs432	I doubt the electrons actually hit, bombard each other, the negative charge in both electrons will force one to move and once they come in close proximity to each other, you know opposite attraction, so I would say conduction through the copper rod by electron transfer, energy of electron transfer, not electron transfer itself.
I-1	So you're saying that the electrons, they actually move further away from the nucleus and because they move away, they're going to interact with
Zqs432	The one above it and the one above it, and as this thing cools down, say it starts approaching room temperature, the electrons that were excited originally, start decreasing in their, I guess their net free path of the nucleus of the copper and as it slows down, the one above it slows down, and they continue to slow down.

In all, the interviews of the four students do allow a better understanding of their concepts as demonstrated on the OEQI. It was found that no significant gain was made by discussing students responses to questions one and two (Figures Two and Three, appendix p. 127), therefore, the decision was made to disregard those responses in future work. Based on the OEQI responses and the interviews, advanced level students have common conceptions with regard to how they describe the atomic mechanisms for heat energy transfer through a material. The students generally know that heat energy from a source will cause atoms or molecules in the rods to become excited and it is the excited state that allows for the transfer of heat energy. The students frequently do not describe what it means to be excited and when they do it is often in terms of either the atoms in the material beginning to vibrate at an increased rate or electrons associated with the atoms moving to a higher state. Those students who picture increased motion believe that the energy is transferred through collisions. When students describe electrons moving to a higher state, they usually state that as electrons move back to the lower state, they release energy and that energy is then absorbed by neighboring atoms and their electrons move to a higher state, the process continues until the heat is transferred through the material. The concept that is not described in either the written responses or interviews is how energy actually gets from atom to atom to atom.

Phase Three: Introductory-level Students' Conceptions of PNM

At this point the types of concepts are known for the populations that participated in the study, but there is a need to collect additional samples in order to establish generality among the different groups. Another introductory level group of students was surveyed using the OEQI format during the spring semester 2002 at the mid-western college (n=26). During this same period of time, it was decided to create a coding scheme that incorporated and refined the common conceptions found in both samples investigated so far, and use this coding

scheme for the new data. For the new coding scheme, there were many concepts that were similar or the same between introductory and advanced students. Those codes that shared similar characteristics were combined into one code that represented the concepts in both groups. Through the combination process, a pattern was discovered among the new codes. The representative codes fell into one of three categories: 1) PNM concepts of heat transfer, 2) PNM concepts of materials, and 3) general concepts of PNM. The resulting coding schemes can be found in Tables Five through Seven respectively.

Table Five: PNM concepts of heat transfer

PNM concepts of heat transfer	
E1	Heated or excited atoms carry heat through the rod
E2	Heated or excited electrons carry heat through the rod, or by the flow of electrons
E3	Heat is passed from atom to atom
E4	Heat is passed from electron to electron
E6	Separate treatment of electrons without a description of interactions of the nucleus
E17	The rod becomes hot because of a chemical reaction with the water
E26	Heat is transferred through a material by non-specific atomic interaction
E27	Heat is transferred through a material by non-specific electronic interactions or electrons responsible for heat transfer
E28	Heat or energy is transferred through collisions or other physical interaction of atoms or electrons
E32	Heat or energy increases atomic interactions
E33	Heat or energy decreases atomic interactions
E34	Different mechanisms or conditions for heat and electricity transfer are described
E35	Heat and electricity are transferred by the same mechanism or because of similar conditions (i.e. metal's properties).
E39	Heat from water melts the butter directly
E42	Non-specific differences in the way electricity and heat are transferred
E43	Heat is transferred so that equilibrium can be reached or maintained
E47	Intermolecular forces described as electrostatic

Table Five (continued)

E48	Heat and electricity are both forms of energy, therefore, ease of transfer is the same
E49	Materials conduct heat for non-specific reasons
E50	No evidence of a nanoscopic description

Table Six: PNM concepts of materials

PNM concepts of materials	
E14	An explanation for the phenomenon is based on person experience or examples.
E18	Differences in conductivity rates based on specific heat, heat capacity, or thermal values or just because one material is a better conductor than another.
E19	Material conducts heat or energy better if the atoms or molecules that make the materials are easier to excite than others or can move faster.
E20	Nanoscopic reasons given for ease of excitement.
E21	Materials made of heavier or larger atoms or more atoms present are harder to heat up or takes longer because heavier atoms are harder to get moving or it takes more energy to get increased numbers of atoms moving.
E22	Material conducts heat or energy better if the atoms or molecules that make the materials have more room to move, decreases the inhibition of heat or energy transfer.
E23	Density inhibits transfer of heat, whether because of tighter bonds between atoms or less room for atoms or electrons to move.
E24	Density promotes transfer of heat, whether because of tighter bonds between atoms or increased interactions because of the proximity of atoms to one another.
E25	Material conducts heat or energy better if the electrons in the materials are easier to excite or if electrons are free to participate in the transfer.
E30	Differences in materials at the macroscopic level with no specific description of interaction.
E31	Differences in materials at the nanoscopic level with no specific description of interaction.
E54	Material's structure relates to the ability of the material to conduct heat energy.
E55	Specific nanoscopic difference or reasons for transfer are described.
E56	Heat causes atoms or molecules to expand.

Table Seven: General PNM concepts

General PNM conceptions	
E7	As atoms move or increase movement the resulting motion increases the overall energy or heat
E5	Atom is a single unit (ball model)
E8	Atoms in solid are not moving before energy (as heat) is introduced
E9	Heat results in increased motion (whether described as vibrational or "excited") of atoms
E10	Heat results in increased motion (whether described as vibrational or "excited") of electrons
E11	Heat causes either atoms or electrons to increase in energy levels
E12	Heat causes electrons to promote to a higher orbital or excited state.
E13	Atomic motion described as vibrating
E15	Higher energy state causes bonds in either the material or target to break or causes the atoms to break away.
E16	Bonds in matter are weakened by an increased motion
E29	Collision described as repelling of electrons
E36	Electricity is a form of heat or electricity gives off heat
E37	Heat is kinetic energy
E38	Heat causes electrons to expand.
E40	Heat increases atomic interactions or forces
E41	Motion described as other than vibrational
E44	Heat is used to mean the average kinetic energy
E45	Collide or collision or terms of physical interaction (i.e. bump) is used with no specific description or meaning.
E46	Heat decreases intramolecular interactions or forces
E51	Application of the kinetic molecular theory of gases to solids.
E52	No codes from scheme apply.

To test whether the new scheme worked with the phase two data, the data was recoded using the new scheme and it was found that the emerging concepts did not change. The new coding scheme will be referred to as the emergent coding scheme. The recoded data results are found in Tables Eight and Nine.

Table Eight: Phase 2 introductory level data recoded using emergent coding scheme

Intro-level														
Set 1 n=41	Code	Freq		Code	Freq		Code	Freq		Code	Freq		Code	Freq
Q1			Q2			Q3			Q4			Q5		
	E15	1					E1	1		E1	1		E34	1
	E2	1		E2	1		E16	1		E22	1		E14	3
	E43	1		E50	40		E17	1		E24	1		E52	5
	E56	1					E23	1		E9	1		E35	7
	E30	2					E40	1		E25	2		E48	31
	E39	2					E5	1		E23	3			
	E18	3					E8	1		E19	8			
	E49	37					E10	2		E30	10			
							E11	2		E31	13			
							E37	2		E18	25			
							E38	2						
							E13	3						
							E2	3						
							E15	4						
							E28	4						
							E3	4						
							E45	5						
							E7	5						
							E51	7						
							E26	11						

Table Nine: Phase 2 advanced level data recoded using emergent coding scheme

Pchem														
n=27	Code	Freq		Code	Freq		Code	Freq		Code	Freq		Code	Freq
Q1			Q2			Q3			Q4			Q5		
	E15	1		E10	1		E10	1		E1	1		E31	1
	E26	1		E13	1		E11	1		E21	1		E36	1
	E51	1		E18	1		E12	1		E22	1		E34	2
	E9	3		E32	1		E16	1		E14	2		E42	2
	E43	2		E9	1		E18	1		E30	2		E52	3
	E52	2		E7	2		E19	1		E19	3		E14	4
	E49	17		E49	3		E2	1		E28	3		E48	5
				E43	5		E21	1		E24	4		E35	12
				E26	6		E22	1		E25	4			
				E50	17		E50	1		E51	5			
							E7	1		E31	8			
							E27	2		E50	8			
							E45	2		E18	27			
							E24	3						
							E3	3						
							E43	4						
							E13	6						
							E51	7						
							E26	9						
							E28	11						
							E9	11						

Based on the results obtained using the emergent coding scheme on the phase two data, the decision was made to code phase three data with this scheme as well. The results of the coding process can be found in Table 10.

Table 10: Phase 3 introductory conceptions coded with emergent coding scheme

Intro-level														
Set 2 n=26	Code	Freq		Code	Freq		Code	Freq		Code	Freq		Code	Freq
Q1			Q2			Q3			Q4			Q5		
	E15	1		E51	1		E11	1		E51	1		E42	1
	E9	2		E50	26		E15	1		E23	2		E36	2
	E49	25					E19	1		E21	3		E52	2
							E2	1		E22	3		E14	3
							E23	1		E24	3		E48	10
							E24	1		E31	4		E35	11
							E28	1		E19	5			
							E3	1		E50	6			
							E45	1		E18	17			
							E52	1						
							E53	1						
							E13	2						
							E51	2						
							E56	3						
							E7	4						
							E26	8						
							E9	20						

Final data

Phase Three: Physical Chemistry Students' Conceptions of PNM

With the results of the first set of physical chemistry data, it was speculated that it might be interesting if physical chemistry students' concepts could be evaluated as the students progressed through the course. In order to do this, it was arranged to have a lecture class of physical chemistry students (n=26) students view the Pasta Lab and complete the OEQI before instruction, approximately half way through the course, and then toward the end of the course. The Pasta Lab was only demonstrated at the beginning and was not repeated for the mid-semester and end of semester data collects. The responses were collected during the fall semester, 2002. The responses for the mid-semester collect were organized with the instructor so that relevant thermodynamic concepts were covered before completing the OEQI for the second time. It is important to mention that after the pre-instructional data was collected and analyzed, questions one and two were dropped from further collects and are not reported here because the questions were not providing interesting data about students' particulate concepts. Also, throughout the course the number of participants drops, mainly due to students who dropped the course and those who did not attend class on the day of the collects. The results are found in Tables 11-13.

Table 11: Physical chemistry students' PNM conceptions pre-instruction

Pchem								
Pre n=26	Code	Freq		Code	Freq		Code	Freq
Q3			Q4			Q5		
	E11	1		E13	1		E14	3
	E12	1		E27	1		E34	3
	E18	1		E54	2		E36	4
	E40	1		E19	3		E48	6
	E43	1		E55	3		E35	12
	E50	1		E30	4			
	E54	1		E31	6			
	E55	1		E25	7			

Table 11 (continued)

	E56	1		E50	8			
	E8	1		E18	11			
	E3	2						
	E25	3						
	E31	3						
	E10	4						
	E13	4						
	E26	4						
	E28	6						
	E51	6						
	E27	7						
	E9	10						

Table 12: Physical chemistry students' PNM conceptions mid-semester

Pchem								
Post A n=17	Code	Frequency		Code	Frequency		Code	Frequency
Q3			Q4			Q5		
	E3	1		E28	1		E34	1
	E33	1		E33	1		E52	1
	E7	1		E45	1		E48	4
	E10	2		E51	1		E35	11
	E18	2		E52	1			
	E43	2		E25	2			
	E45	3		E26	2			
	E50	3		E50	2			
	E13	4		E55	2			
	E26	6		E19	4			
	E28	6		E31	4			
	E51	6		E18	12			
	E9	11						

Table 13: Physical chemistry students' PNM conception end-semester

Pchem								
Post B n=16	Code	Frequency		Code	Frequency		Code	Frequency
Q3			Q4			Q5		
	E11	1		E15	1		E14	1
	E18	1		E21	1		E36	1
	E2	1		E28	1		E52	1
	E27	1		E51	1		E48	2
	E30	1		E7	1		E34	4
	E3	2		E19	2		E35	9
	E31	2		E24	2			
	E43	2		E31	3			
	E7	2		E54	3			
	E10	3		E55	3			
	E13	4		E50	4			
	E26	7		E18	6			
	E28	7		E25	6			
	E45	7						
	E51	8						
	E9	9						

To get an overall appreciation for the changes in concepts that take place during the semester, results for each question are compared in Table 14. Only the students responses which included pre and at least one set of post instructional responses were analyzed for a final number of 19 respondents.

Table 14: Comparison of PChem concepts during semester by student and question

Student	Pre Code Q3	Post-A Code Q3	Post-B Code Q3	Pre Code Q4	Post-A Code Q4	Post-B Code Q4	Pre Code Q5	Post-A Code Q5	Post-B Code Q5
0848	E27 E43	E9 E43 E26	E26 E28 E43 E45 E51	E18 E25	E18 E31	E18 E21 E50 E51	E35	E48	E34
1117	E27 E10	E9 E13 E26	E7 E9 E13 E28 E45	E18 E25	E18 E55	E18 E24 E54 E55	E35	E34	E14 E34

Table 14 (continued)

1553	E18 E31	E9 E28 E51	E9 E31	E18 E50	E18 E28 E31 E45	E18 E31	E14	E48	E36 E48
2088	E9	E10	E30 E51	E55 E18	E19	E19 E31	E48	E35	E35
2236	E54 E51 E55	E13 E18 E26	E18 E31	E19	E18 E19 E31	E50	E34	E35	E48
2689	E10 E13 E27	E10 E28 E45 E51	E10 E27 E28 E45 E51	E25 E27	E18 E25	E25	E35	E35	E35
2975	E28 E51 E13	E18 E50	No data	E31	E52	No data	E36	E52	No data
3324	E9 E13	E9 E26	No data	E18 E13 E19	E18 E19 E26	No data	E48	E35	No data
3457	E9 E31	E9 E7 E26	E26 E28 E45 E51	E31	E31	E18 E50	E48	E35	E35
3623	E9 E13 E26 E26	No data E3	E13 E26 E51 E9	E50 E30	No data	E25 E54	E35	No data	E35
5601	E10 E28 E51	E9 E28 E51	E3 E9 E26 E28 E45 E51	E18 E25	E18 E55	E24 E54 E55	E35	E35	E34
6572	E10 E27	No data	E9 E43	E25 E30	No data	E18 E25	E34	No data	E34

Table 14 (continued)

6678	E25 E27	E9 E28 E45 E51	E7 E9 E13	E31	E18 E50	E50	E35	E35	E52
6744	E9 E12	E9 E28 E13 E51	E2 E3 E9 E26 E28 E45 E51	E18 E54	E18 E51	E18 E25 E55	E35	E48	E35
7728	E9 E50	E9 E13 E33	E13 E26 E9	E18 E31	E33	E15 E19	E34	E35	E35
8359	E28 E51	E50		E31 E25	E18 E50		E35	E35	
8659	E11	E43 E50	E10 E11	E50 E30	E25	E25	E48	E48	E35
8993	E9 E26 E40	E9 E28 E45 E51	E28 E45 E51	E18 E50	E18 E19	E28 E31 E7	E35	E35	E35

Discussion of Physical Chemistry Students' Phase Three Responses

It was anticipated that the advanced level students taking thermodynamics for this sample would share many of the same concepts with introductory level students before instruction and that particulate concepts would become refined through the course of study. The interpreted data suggests that there are conceptual changes made along the way. An analysis by student and question follows:

Student 0848:

Q3: This student expressed the idea prior to instruction that heat travels through a material by electron interactions: "The excess heat energy is stored in the electrons of the atoms…". The student did not offer an explanation of how the energy gets through the rod. By the first retest, this student brings about ideas of nanoscopic motion: "As more energy is added to the atoms (in the form of heat), they begin to move faster and faster. As they do so, heat is transferred from one atom to the next…". Although it seems that the student does have a better particulate concept, the interactions responsible are still not discussed. The student abandons this line of thinking by the end of the semester stating the "before the rods are placed into the hot water, they are in thermal equilibrium. To say this means that there is a Boltzmann distribution of the velocities of the atoms in the rod… the equilibrium is disturbed, and the distribution has to realign itself. This is caused by the atoms in the solid colliding with each other at a higher rate than before…" The student has begun to apply the kinetic molecular theory of gases to solids, which has been identified by others as a misconception [10]. The student progresses from having a particulate concept not too far from correct scientific belief to one that, although more elaborate, incorrectly applies a basic model.

Q4: During the course the student sticks with the belief that different specific heat capacities of the materials are responsible for materials conducting heat at different rates. The question specifically asks for an atomic level explanation for

this; however, one is not offered by the student during the course of study. By the end of the course, the student does offer an explanation consonant with the inappropriate application of kinetic molecular theory to solids: "This is because $u = 1/2\ mv^2$, and with the heavier metals, it was harder to move the particles." Further, the student's explanation does not make sense based on the observation (available to the student) that copper and aluminum have the fastest rates of heat transfer and titanium, for example, is slower.

Q5: The student shows some change in the answers throughout the semester for this question. For the pre-instructional response, the student says "yes, because electricity is the flow of electrons. The atoms with loosely held electrons (Cu, Al) transfer them easier, and therefore conduct electricity better." By the end of the semester, the student says that "good conductors of heat are also good conductors of electricity…in metals, electrons float around in a sort of fixed matrix, not bound to any particular atom, this makes the flow of electricity easier. The electrons move around with some Boltzmann distribution, and as more electrical energy is applied, it flows from one end to the other as the electrons redistribute the distribution". One can see that the underlying concepts are the same; however, the student is able to use the language picked up in the thermodynamics course with expressing particulate concepts.

Student 1117:

Q3: This student also started out with a nanoscopic concept involving electrons, stating that "the water molecules excite the materials electrons, causing movement of electrons (heat transfer). This continued through the material's atoms until it reaches the butter." It is again evident that the student uses nanoscopic terminology but does not explain a mechanism for the transfer of heat. This student also discusses movement on the atomic level, specifically mentioning vibrations: "Water molecules vibrate and gain velocity as the temperature rises. As the water molecules come in contact with the atoms of the metal rods, those atoms began to vibrate (heat the material) along its length until eventually the butter atoms on the surface were excited enough to change state."

This student's concept does not change significantly by the end of the semester, still believing that "...the molecules in the metal vibrate against each other, making the rod heat up..." In both cases, the student seems to think that its atoms vibrating against each other that heats the rod, which in turn melts the butter. It appears that this student does not have a metal model of how forces between atoms in the solid are responsible for heat transfer. What is interesting is the appearance of the concept of physical contact between atoms in the material, again appearing toward the end of the course.

Q4: The student gave responses to this question at both the macroscopic and nanoscopic levels. The macroscopic answer was simple because "...some materials conducted heat better than others..." At the nanoscopic level, the student explains that "...the bonding of electrons helps or inhibits their movement, causing heat transfer to happen faster or slower. (inhibit→covalent, help→ionic)". The mid-semester response for this question was not much different: at the macroscopic level "because the heat capacity of some metals is larger." At the nanoscopic level: "some metal's lattice structures are more closely packed, allowing for easier conduction on the molecular level." The student follows the same line of thought by the end of the semester. Even though the student uses particulate concepts, they are incomplete in that the student does not discuss how these characteristics would help or hinder energy transfer, leading to the belief that the student does have difficulty with thinking about particulate concepts involved in heat transfer. This is o.k. and expected, the point was to see if the PNM concepts the students use are sound.

Q5: The student's pre-instruction response reflects the belief that electrons are responsible for heat conduction: "Yes, because electricity conductivity also depends on electron movement". The student's reasoning has not changed by mid-semester: "Yes, electrical conduction is related to heat conduction. As one gets larger because of free electrons from atoms, the other gets larger because of decreased spacing of atoms in lattice structures." One can see that the student is also incorporating the thought that lattice structure has something to do with a material's ability to conduct heat. It is apparent that the student is

unsure of what to think by the end of the semester: "...on the atomic level, when something is a good conductor of heat, the atoms are close together. On the other hand, for conductors of electricity, the mean free path for electrons must be larger. Therefore technically the atoms would have to be farther apart, or just arranged in a more perfect structure to have higher electrical conductivity."

Student 1553:

Q3: This student starts out with an undefined particulate view: "...different materials conduct heat more rapidly than other materials." (S)he then tries to reason why this might be, "This causes the atoms of some materials to move more quickly than the atoms of other materials. This produces more kinetic energy in the atoms and causing the heat to travel more quickly as was the scenario with the Cu rod. Copper conducts heat more readily than the other rod materials." Although particulate terms are used, there is very little that would be classified as understanding the particulate nature of matter. The student transitions to a more particulate conception, but there is misapplication of the kinetic molecular theory of gases: "...the atoms of the butter start to move as more heat travels to the butter the atoms move faster and more collisions are made between the atoms." By the end of the semester, the student abandons a particulate explanation: "The energy of the atoms goes from potential energy to kinetic energy as the heat travels from the hot water to the butter." The reasons for this type of answer are unknown, perhaps the student's dissatisfaction with the first two iterations lead the student to try and apply a totally different concept in trying to explain the process of heat transfer.

Q4: The student gives the macroscopic reason of different thermal conductivities being responsible for the different rates of heat transfer. The nanoscopic explanation for this resembles the responses to question three, if atoms move more rapidly, for unspecified reasons, the heat is transferred faster. By mid-semester, the student gives a slightly different nanoscopic explanation which introduces physical contact: "On the atomic level, the rods made of higher thermal conductivity had more atomic collisions within the butter on top of these

rods." The end of semester response does not change except for the exclusion of the idea of collisions: "On the atomic level the rods with the higher thermal conductivity had a higher kinetic energy of the atoms and therefore heated up faster to melt the butter sooner."

Q5: The student relies on personal experience to answer the question: "Yes, because I know from experience that copper is used in wires to conduct electricity. For example, in my car-the fuse box. Electricity produces heat." This is an interesting response, even though there is no evidence of particulate conceptions, the student relies on everyday "common sense" knowledge. By mid-semester, the student simply states "Yes, because they are the same." By the end of the semester, particulate reasoning is still not evident: "Yes, electricity is a form of heat. Electricity gives off heat. So a rod that is a good heat conductor would also be a good electricity conductor." This student over the semester does not show particularly strong particulate concepts, again emphasizing that some students may have trouble thinking about nanoscopic interaction of atoms and molecules.

Student 2088:

Q3: This student does not demonstrate a particulate concept despite the mention of the term atom: "The atoms are getting excited as the heat travels up the rod. This is why expansion also occurs in the rods with addition of heat." This response shows how students apply macroscopic reasoning to something that requires nanoscopic concepts. This may indicate that because there is not a meaningful particulate concept on which to draw, the student uses something familiar, objects expanding when heated, and applies it to the nanoscopic level. The student expresses a different concept by mid-semester: "The electrons are being excited and the heat travels from the higher energy material to the lower energy material". By the end of the semester, the student substitutes thermodynamic concepts for particulate explanations: "...as the heat transfers and work is done on the atmosphere, the sum of these numbers equal the internal energy. The enthalpy is equal to the internal energy and the product of

the change in pressure and volume on the atomic level…" The student's responses throughout the semester indicates that (s)he did not develop deeper particulate concepts.

Q4: It is not surprising that this student, who seems to have difficulty with particulate concepts, gives this reason for different materials having different transfer rates: "Certain elements have properties of conductivity that differ. Conductivity depends on molecular or atomic weight, bonding, and several other properties…" The reasoning does not change until the end of the semester: "…the electron configuration plays a big role as well as the actual lattice configuration of the rods. Those rods which have atoms that are more easily excited will transfer the heat more easily to the butter and thus it melts." This response is similar to those previously reviewed in that specific particulate reasoning is not used. The student uses "lattice configuration" without discussing how this might affect a materials heat conducting rates.

Q5: Student 2088 uses reasoning for this question much like those discussed earlier: "Yes, because heat is merely a measure of a form of energy. Electricity is also merely energy…" This reasoning changes very little over the course and the student does not offer a particulate explanation of why or why not heat conductors are good electrical conductors. At this point it seems that students do not or can not differentiate the mechanisms of heat and electrical conduction because the explanation requires a sophisticated particulate view of both phenomena.

Student 2236:

Q3: This student starts the semester with a particulate concept that includes physical interactions of atoms within the material: "The atoms, in their nearly crystalline form, start slamming into each other. The better this kinetic energy is conserved and conducted (as kinetic energy) the better the material is able to conduct heat." It is suspected that this student sees energy being conducted through collisions of the atoms in the material. There is little change to this concept by mid semester, however, the student describes the process in more

appropriate themodynamic terms, relating the reason to thermal conductivity: "We can assume that thermal conductivity's units are something like energy per unit distance per unit time per unit temperature or (in SI) J/M· S · K, so the thermal conductivity of a material is dependant on the ability of atoms to transfer energy from one to another...maybe the atoms energy is translated to vibrations." Here the student is continuing to use the idea of particulate motion, although it seems the student is not sure what it means. By the end of the semester, the student abandons particulate concepts and gives the reason of thermal conductivity without an explanation at the particulate level: "As related to what we've learned in class: thermal conductivity must be related to the heat capacity of materials." The student goes on to describe that the process must involve the discrepancy of the heat capacity of air and the metals. This again can be view as the student's attempt to explain the process of heat conduction using pre-existing particulate concepts and becoming dissatisfied with his/her explanation and by the end of the course has abandoned a particulate explanation altogether.

Q4: The student answers this question by applying their kinetic energy concept: "The kinetic energy of the atoms was more easily conducted through the material." The student does not offer a particulate reason as to how or why this might be the case for the different materials used in the experiment. The student uses the same reasoning for the mid-term response, however, incorporates the term thermal conductivity: "thermal conductivity better in some rods than others. The atoms had an easier time translating KE from atom to atom." For the last set of responses, the student does not attempt to give a particulate explanation for the different heat transfer rates observed in the experiment. The student relates a better conductor of heat to having lost less heat to air than poor conductors, but does not give a particulate reason why this might be the case.

Q5: It is suspected that the student has different mechanisms in mind for heat and electricity transfer, however, is not specific about what those differences are: "Not necessarily. Electrical conductivity is movement of electrons, not entire atoms." The student has a change of perspective by mid semester: "Yes,

electricity conduction is based on similar properties of atoms to translate energy from atom to atom." The student's confidence in his/her answer is not as strong by the end of the semester: "...but it seems that the ability to conduct electricity is still a form of energy that a material must be able to sop up in order to get the distinguished title of high heat capacity. So, I have no idea what I'm talking about".

Student 2689

Q3: The student starts the semester with a sound particulate concept: "The electrons in the outer shells of those atoms [in the metal] begin to vibrate more and transfer the energy to the nearby electrons of the surrounding atoms, and so on, until the top of the rod warms up." What is missing is the description of nanoscopic interactions and a discussion of how the whole atom might be involved in the heat transfer process, but at least the student demonstrates particulate concepts. By mid-semester, it is obvious that the student begins to apply the kinetic molecular theory of gases to explain heat transfer: "Electrons that are in contact with water start to move, collide with other electrons, transfer some energy to them during the collision, then these electrons start to move, and so on." It is interesting that in the first response the student uses "vibrate more", indicating that there is motion present that increases and then says "start to move", indicating that the student may not recognize the motion present originally. The student uses this colliding concept again in the final response: "Electrons at the bottom of the rod absorbed some of the heat energy and started moving faster, colliding into other electrons, transferring some of their energy to those electrons..." This is one of few examples that show a consistent use of the same concept over the course of study, which may indicate that this student strongly believes his/her reasoning fully explains heat transfer.

Q4: Like students discussed previously, this student incorporates the ideas presented in question three into the answers for question four: "[The pasta] fell off Cu first because it must conduct heat the best out of these materials...Cu needed the least amount of energy to excite its electrons, other materials needed

progressively more, and Ti needed the most amount of energy." Although the student recognizes that heat transfer rates might have something to do with the amount of energy, the student does not indicate having a concept of why this is the case. The student repeats the response for the mid-semester and final response, sticking to the reason that "electrons of these metals need less energy to be excited." This reiterates the idea that the student is satisfied with the explanations given and does not see a reason to change the central concept.

Q5: The students first response is based solely on one of the materials used in the experiment: "Yes, copper is a good conductor of electricity. Electric charge is carried by the movement of electrons." The student does indeed believe that heat is carried through a material by electrons, which makes it easier to associate with electrical transfer. The student uses the same reasoning for mid-semester and final responses, stating that "both phenomena are based on the motion of electrons." It is obvious through a review of this student's responses for the three questions over the course that the student has a single unified concept and applies this concept to explain how heat is transferred, why it is transferred at different rates through various materials, and how heat conduction is like electrical conduction. It is this type of student, consistent in their belief, than emphasizes the need to discover students' concept so that true scientific understanding can be relayed through conceptual change.

Student 3623:

Q3: For this student only the pre-instructional and final semester responses are available. The student's initial response does not lead to a clear understanding of his/her particulate concepts: "The atoms get energized by the heat energy they start to vibrate and they hence transfer their energy to the other electrons in the system." It is obvious by the final response that the student has incorporated a kinetic model of gases and uses it to explain heat transfer: "In ideal gases the energy is based upon only the kinetic energy interaction between most molecules. All gases behave ideal at low pressure when the molecules are not close together. In solids the molecules are a lot closer together therefore they

behave far from ideal because the molecules are so close together. Hence the heat was transferred through the metal by the vibration of the atoms…" The student does not indicate physical contact like the previously discussed students, however, it is interesting that (s)he begins the discussion with "ideal gases".

Q4: The student does not provide a particulate description for the differences in materials, stating "better conductors of heat are more sensitive to different changes in the temperature…" The student does come to a particulate description by the end of the semester: "…because of the amount of free electrons and or the crystalline arrangement of the molecules that allows the free arrangement atoms and the electrons are free." Again it seems the student has the idea that electrons are somehow responsible for heat transfer but does not discuss the electrons involvement in the process.

Q5: The student offers a much more detailed explanation for this question in the initial response. The student's response incorporates ideas apparent for the earlier questions: "The mechanism by which heat is transferred is very similar to the way electricity is transferred. Metal are good conduction because of the free electrons in these structure and this is the same thing used to transfer electricity." By the end of the semester, the student provides a simple answer: "Because the transference of heat and electricity are similar."

Student 4991:

Q3: The student demonstrates a limited particulate view in the initial response: "The heat is exciting the atoms causing the heat to be transferred from atom to atom up the length of the rods." The student's use of the term "exciting" or "excite" is something commonly seen among all levels of students involved in this study. The word is used in a context to mean several things: an atom whose electrons reside in a higher orbital, increased motion, and atoms traveling at a higher velocity. This student maintains the use of excited atoms in his/her mid-semester explanation: "The hot water excites the atoms in the bottom of each metal rod. The excited atoms excite other atoms all the way up the rod. These excited atoms give off heat." Present in this response is an alternative meaning

of “exited”, used to describe unspecific interactions of the material’s atoms. Like several of the students discussed previously, this student uses atoms in the explanation but does not discuss how the atoms are involved in the process of heat conduction, indicating a limited particulate view or difficulty thinking about this phenomenon at the nanoscopic level. By the end of the semester, the student incorporates the use of electrons into the explanation: “The hot water excites the electrons in the atoms at the bottom of the metal rods. The excited atoms will excite the other electrons in the atoms up the length of the rod.” It is not apparent whether the student truly thinks electrons are responsible for heat conduction, or has merely substituted the word electrons for atoms.

Q4: The only particulate reasoning this student provides for the initial response is “The pasta fell earlier for some rods than other due to the bonding of atoms-the way the atoms bond to each other.” The final response is more sophisticated, relating fast heat conduction rates to how fast electrons are excited: “The electrons in the atoms are excited faster and the heat moves up the rods through the excited electrons faster in the rods that are hood heat conductors.” The student does not provide a reason that electrons might be more easily excited.

Q5: The student’s initial concept is that “electricity is a form of heat”, therefore metals will conduct heat and electricity. The mid-semester response is somewhat different: “ Yes, due to the way the atoms get excited and give off heat to the surroundings.” The final response again incorporates the use of electrons: “Yes, good conductors of heat can also be good conductors of electricity due to the electrons in the atoms. The electrons will be excited faster in good heat or electricity conductors.”

It is obvious from the examples of student responses that their concepts do change, but not necessarily in the way that a teacher would hope. The students that participated are very near the end of the academic careers and as stated previously, the assumption is that these students have sound acceptable particulate concepts. The reader should be assured that all of the students in the phase three sample not represented here exhibited the same concepts and

explanations as the students discussed above. In general the changes that took place over the entire sample follow:

Q3: There is an overall decrease in the number of students who at the onset use ideas about non-specific interactions of atoms or electrons. It appears that toward the end of the course, the students begin to use the ideas of atoms or molecules in the solid colliding and thereby transferring heat energy, symptomatic of use of ideal gas examples in the study of thermodynamics. Students in thermodynamics spend most of the course talking about ideal gases. Students seem to ignore the fact that there are no rotational or translation movements, only vibrational, and it is only through this motion that energy can be transferred. It is also interesting that students transition from basic particulate views involving atoms to those involving electrons. It seems that the mechanism responsible for electrical conduction can be applied to heat using existing particulate concepts. The most significant finding is that there were no instances of students starting out with a limited particulate concept and then demonstrating a complete particulate concept by the end of the course.

Q4: Students at the onset believe that heat transfers through materials faster based on their conductivities; however, they do not try to explain what it is about the material's nanoscopic properties that is responsible for this observation. By the end of the semester, students do try to explain the characteristics responsible. Most attribute to the ease in which either the atoms or electrons in the material can be excited. Even though there is an exchange of macroscopic concepts for nanoscopic concepts, the concepts only go as far as to mention the involvement of nanoscopic entities without being specific as to the nature of those entities.

Q5: There are no major changes in concepts that take place for this question. This may be indicative of how deep the concepts of electricity are and how the comparison made earlier between heat and electricity really does depend on deep rooted common sense rather than knowledge developed in science classes.

Misconceptions of Students Concepts

Much of the reviewed literature does not take the approach that is taken for this study. Instead of identifying shared conceptions among a student population, most research looks only at conceptions that do not parallel scientific thinking. In the interest of being able to compare the populations represented in this study with those found in existing literature, a coding scheme was created using the misconceptions from the literature. First, all of the misconceptions listed or described in the reviewed literature were compiled into a database. The like concepts were then given the same code, however, the definitions for the codes includes all forms and examples found in the literature. The misconceptions based coding scheme, referred to as the derived scheme, was applied to all student data collected during phases two and three. A table of reviewed literature and misconceptions is found in Figure Six (Appendix, p. 129) and the coding scheme is found in Table 15. The results of the coding is found in Tables 16-18.

Table 15: Derived code scheme definitions

G1:	
	M & R 1. Subject responses do not conserve atoms
	A & W 1. Lack of conservation of atoms.
	G,S, & H 1. No conservation of particles.
G2:	
	B, E, & S 1. No distinction between properties of a substance and those of a single isolated atom.
	B, E, & S 5. Single atom can conduct electricity.
	B, B, & D 3. Application of macroscopic characteristics (size and temperature) to particles.
	N & S 1. Macroscopic properties associated with nanoscopic entities
	N & M 8. Particles or molecules of solids are hard and that of liquids and gases are soft.
	N & M 13. Particles or molecules get soft when matter melts.
	N & M 22. Solids are made of hard types of molecules.
	W 2. Macroscopic properties attributed to nanoscopic entities.
	W 4. Gas particles are light.

Table 15 (continued)

	H 1. Generally many episodes of subjects associating macro level characteristics to particles.
	B, E, & S 2. An atom of gas can be compressed.
	L et al 4. Associated macroscopic properties to atoms and molecules
G3	
	W 1. Heated particles expand.
	B, B, & D 5. Particles expand and exert forces on each other upon heating.
	B, E, & S 3. An atom of gas expands when heated.
	G & P 17. Heat results in a change of atomic size.
	G & P 3. Heat causes molecules to expand leading to separation of molecules during melting.
	G & P 6. Heat causes molecules to expand.
	N & M 2. Particles or molecules get bigger, expand when heated.
G4	
	B, E, & S 4. Gas atom larger than solid atom.
G5	
	N & M 3. Particle or molecular sizes, shapes and numbers change during melting or heating.
	N & M 5. Particles or molecules shrink when cooled.
G6	
G7	B-Z & G 1. No change in atomic or molecular motion as heat is added to a system.
	B, B, & D 2. Decrease in temperature of a substance decreases the forces exerted between particles of that substance.
G8	
	B, B, & D 4. No appreciation of the intrinsic motion of particles
	L et al 2. There is no motion associated with molecules in a solid
	N & M 14. Molecules do not move in matter, especially in solids.
	N & N 1. Subject across age groups have a static particle picture.
G9	
	B, B, & D 6. Misapplication of the kinetic molecular theory; solid state is likened to the gaseous state or to the liquid state.
	B, B, & D 7. Particles can move freely in a solid.
G10	
	G & P 1. There is only one kind of atom.
G11	
	G & P 2. All the atoms in a molecule are the same
G12	
	G & P 4. The speed of a molecule is determined by its size.
G13	
	G & P 5. The more space a molecule has to move the faster it will move.

Table 15 (continued)

G14	
	G & P 8. An atom resembles a solid sphere.
G15	
	G & P 9. An atom looks like several dots/circles.
G16	
	G & P 10. Electrons move in orbits.
G17	
	G & P 11. Atoms are flat.
G18	
	G & P 12. Matter exists between atoms.
	L et al 1. Something exists between molecules in a substance
G19	
	G & P 13. Atoms are large enough to be seen under a microscope.
	N & M 9. Particles or molecules can be seen with or without a microscope.
G20	
	G & P 14. Atoms are larger than molecules.
G21	
	G & P 18. Collisions result in a change of atomic size.
G22	
	G & P 15. All atoms are the same size.
G23	
	G & P 16. The size of an atom is determined primarily by the number of protons.
G24	
	G & P 19. All atoms have the same weight.
G25	
	G & P 20. Atoms are alive.
	G & P 21. Only some atoms are alive.
	G & P 22. Atoms are alive because they move.
G26	
	H & A 2. Belief that heat is a substance that can be attracted, absorbed, and can even take up space.
G27	
	N & M 1. Particles or molecules become bigger when matter dissolves.
G28	
	N & M 4. Different states of the same substances have differently shaped particles or molecules.
G29	
	N & M 6. Particles or molecules gain weight when heated.
G30	
	N & M 7. Particles or molecules get bigger when matter freezes.
G31	

Table 15 (continued)

	N & M 10. Matter made up of something other than atoms or molecules
G32	
	N & M 11. Solids do not have space between their molecules.
G33	
	N & M 12. There is friction between molecules which generates heat.
G34	
	N & M 15. Particles or molecules move and make their own energy.
G35	
	N & M 16. Particles or molecules in all states of matter possess the same temperature and pressure.
G36	
	N & M 17. Particles or molecules move as a result of collisions between themselves.
G37	
	N & M 18. Energy of molecules originate from gravity.
G38	
	N & M 21 Molecules exist only in substances that can be broken down into powder form.
G39	
	N & M 23. Equal volumes of any combination of phases of matter contain the same amounts of molecules.
G40	
	N & M 24. Gases have more molecules per unit volume than other substances.
G41	
	N & M 25. Particles or molecules of solids are smaller than that of other liquids and gases.
G42	
	N & M 26. Solids have the largest particles or molecules followed by liquids and gases.
G43	
	N & N 3. The particle model only holds for gases; liquids and solids are continuous.
G44	
	W 3. Constant force(s) are required to keep particles moving.
G45	
	W 6. The speed of a particle of gas is dependant on pressure or volume.
G46	
	B, B, & D 1. As temperature of a substance decreases, particle speed increases.
G47	
	G,S, & H 2. The enlargement of atoms as they change from liquid to gas.
G48	
	G,S, & H 3. Gas particles are arranged orderly in space.
G49	

Table 15 (continued)

	G & P 7. An atom resembles a sphere with components inside.
G50	
	H & A 1. Lack of a model of interaction (attraction and repelling forces) between molecules
	N & M 20. Nothing holds molecules together in any given substance.
	N & N 2. Attractive forces between particles of a gas increases and accounts for the decrease in volume.
G51	
	L et al 3. Molecules begin to move when external forces are applied
G52	
	H & A 3. Molecules begin to move when external forces are applied
G53	
	N & M 19. Molecules stop to move when substances are frozen solid.
	Key: M & R: Mulford & Robinson [79] A & W: Abraham &Williamson [3] B, E, & S: Ben-Zvi, Eylon, & Silberstein [7] B, B, & D: Brook, Briggs, & Driver [10] G,S, & H: Gabel, Samuel, & Hunn [17] G & P: Griffiths & Preston [18] N & M: Novak & Musonda [81] N & S: Nakhleh & Samarpungavan [55] N & N: Novick & Nussbaum [50] H & A: Haidar & Abraham [58] W: Whiteley [34] B-Z & G: Ben-Zvi & Gai [49] L et al: Lee, Eichinger, Anderson, Berkheimer, & Blakeslee [19] H: Happs [86]

Table 16: Combined findings using derived coding scheme for question three
Note: G54 is added by the author to indicate no other codes apply

Intro Phase 2 Q3		Intro Phase 3 Q3		Pchem Pre Q3	
Code	Freq	Code	Freq	Code	Freq
G3	1	G51	1	G53	1
G34	2	G33	2	G9	5
G9	3	G3	3	G54	20
G54	33	G54	20		
Pchem Post A Q3		Pchem Post B Q3		Pchem Phase 2 Q3	
Code	Freq	Code	Freq	Code	Freq
G33	1	G9	5	G51	1
G9	6	G54	11	G9	3
G54	10			G54	23

Table 17: Combined findings using derived coding scheme for question four
Note: G54 is added by the author to indicate no other codes apply

Inure Phase 2 Q4		Intro Phase 3 Q4		Pchem Pre Q4	
Code	Freq	Code	Freq	Code	Freq
G54	41	G12	1	G3	1
		G54	25	G54	25
Pchem Post A Q4		Pchem Post B Q4		Pchem Phase 2 Q4	
Code	Freq	Code	Freq	Code	Freq
G9	1	G9	2	G51	1
G54	16	G54	14	G54	26

Table 18: Combined findings using derived coding scheme for question five
Note: G54 is added by the author to indicate no other codes apply

Inure Phase 2 Q5		Intro Phase 3 Q5		Pchem Pre Q5	
Code	Freq	Code	Freq	Code	Freq
G54	41	G54	26	G54	26
Pchem Post A Q5		Pchem Post B Q5		Pchem Phase 2 Q5	
Code	Freq	Code	Freq	Code	Freq
G54	17	G54	16	G54	27

As can be seen from the results of applying the derived coding scheme, there were very few incidents where students' concepts from this study would be considered as misconceptions according to the literature definitions. The more frequent concepts found across the entire study population that are considered to be misconceptions by the literature are that atoms or molecules expand when heated and students' misapplication of the kinetic molecular theory of gases to solids. Both have surfaced and been discussed earlier in this paper.

Interviews as a Method to Evaluate Misconceptions

It was noticed that many authors whose work generated lists of misconceptions prevalent in this study's population did not use semi-structured interviews as a way to triangulate data. Physical chemistry students that participated in the fall 2002 OEQI data collection were asked to participate in interview using the same protocol as before. The purpose of this round of interviews was not so much to see what their concepts were, but to see if the concepts that they used on the written responses would be the same in an interview setting. This is especially helpful when students concepts have been deemed misconceptions; talking to a student face-to-face allows the researcher to find out what students really mean when they use language like "expand" and "collide". Nine students participated in the interview portion of the study.

The issue of expanding atoms and molecules was approached by having the interviewee evaluate a student's response (Figure 3, appendix, p. 111) that discusses atoms expanding. Out of the nine students interviewed, seven of the students stated in various ways that they do not believe atoms can or do expand:

I-1	And we're asking them, basically the same things that, you know, we want to know the same things from them that we want to know from you, how do you
0848	Right.
I-1	Think about that on a subatomic level
0848	Um hmm.
I-1	How these things, how this heat is being transferred through.
0848	I think pretty much with that first sentence, um, the person might mean how, when they, on the second sentence, as atoms get hotter they expand. Um, they don't expand, they would just vibrate back and forth, so them becoming closer together, that's, you know that closer together and farther apart, so that's, I don't know, I'd suppose half right and half wrong.
I-1	Okay.
0848	But, it's a pretty astute observation though.
I-1	So, it's, especially the first sentence, you're thinking it's, they're maybe have in their mind this motion,
0848	Right.
I-1	You describe this as vibrational?

I-1	Just go ahead and read the responses and then we'll talk about them.
1117	All right, well I think with this first one, it seems like, they've got the idea that when something heats up, in general it expands, but I think it seems like they don't quite understand what's actually expanding.
I-1	Okay.
1117	That what they've got here is that the atoms, what it seems like they're saying is that the atoms get bigger themselves
I-1	Um hmm.
1117	Instead of moving farther apart, because they have more energy, they are bouncing at each other and colliding and moving farther apart. Um, and then when it gets to this next sentence, it says so when one hot atom touches a cool atom, the hot atom heats up the cool atom until the atoms are heated up, that's that's what's happening, but not exactly in the way, like they're, they're seems that they understand that the heat is going from the hotter part
I-1	Okay, how is it that you could see somebody thinking that?

1553	Um, when something is heated up, one might think that atoms might gather together, that are being close, that are being separated.
I-1	Um hmm.
1553	And then as the atoms get hotter, they expand. That makes me think that maybe their thinking that as the atoms get hotter, they're growing in size.
I-1	Um hmm.
1553	The heat makes the atoms grow bigger.
I-1	Right.
1553	So when one hot atom touches a cool atom, the hot atom heats up the cool atom, so the atoms are heated enough to work their way to the top of the rod and melt the butter. Okay, so they're saying that first you start out they are close together, then as it gets hotter, they become bigger, and I guess they spread out, or they either spread out or expand in size with those.
I-1	Um hmm.
1553	Either one. They just, they expand. I don't know which one that is. Um, then I guess they just rise up.

I-1	Do you think they are talking about the whole atom beginning, or do you think it's important to make that separation there?
2689	Um, I think what they're imagining is an atom is a ball, that's what I get on expression. Uh, is a sphere that expands and that's not really true, an atom is a nucleus and electrons surround it.
I-1	Okay, so um, when they say it expands, what do you think they're talking, so you said that atoms cannot expand, it's just the electrons right?
2689	Well, if you think of an atom gaining an electron and um losing an electron, I guess from that point of view they can expand and

	contract, but since the metal electrons are not really assigned to a specific atom.

I-1	Let's talk, they talk about um an atom being able to expand, what do you, what do you think about that?
3623	No atoms can't expand, they just receive the energy and get more active.
I-1	What do you mean by more active?
3623	When … I mean they get, I mean this … increases.

I-1	Okay, let me ask you, the way you think about expand, what does expand mean to you?
4991	Getting bigger.
I-1	Okay, in what way, do you think that,
4991	Like a balloon,
I-1	Is it particular to the atom?
4991	When you expand a balloon, it gets bigger and when you talk about an atom, I'm not really sure what she's trying to say.
I-1	Now are you thinking, when you think about, do atoms have that ability as they're heated up, they can expand and get bigger, like the balloon?
4991	No, usually, when they get heated up the electrons in the outer shell get excited, it's not really expanding the shell, or the atom.

I-1	Yeah, a couple things in that statement I want you to concentrate on, first um, um, they're talking about this thing, the atoms get hotter and they expand.
6572	Well first of all, the atoms don't get hotter, uh, temperature is based on like … movement, average kinetic energy, uh so, I guess that's wrong. Uh, they expand? I think, I'm not to sure what they're talking about, expansion, if they're talking about relaying one atom to another atoms distance, yeah that's true, when things are heated up they move at a different rate, and they're further apart, like the solid atoms are crystallized and get closer together, um, so I guess, you know, they're conclusion is wrong because based on the introduction it's wrong, you know what I mean?
I-1	So basically atoms don't expand themselves, but they get further apart, is that what you're saying?
6572	Yeah, they don't expand themselves, I don't think at least.

As can be seen from the interview sections, students for the most part in this sample do not believe atoms can expand. It is possible that those who reported

this misconception in the literature might benefit from talking with students to ensure their interpretation of the students' view is correct.

Concept of collisions:

Most students brought up the concept of atoms colliding when thinking about how heat energy is transferred through the material on a particulate level. When students were asked to focus on what it meant for atoms to collide, they had the following to say:

After student 2689 has indicated that electrons are responsible for heat transfer and that the energy is transferred through collisions:

I-1	Kind of describe for me what you think when you say electrons are colliding? If you could have two electrons, well, let me hear what you have to say about it?
2689	Um, hmm, um, they come together to a close distance and then forces of repulsion come into play, they don't actually touch.
I-1	Okay. So when one comes in proximity to another
2689	Right.
I-1	It kind of electromagnetic repulsion pushes it away.
2689	Right.
I-1	Okay, so they're not actually
2689	No physical contact.
I-1	No physical contact, okay.
2689	Right.

After prompting student 3623 to describe how energy is transferred from one atom to another:

I-1	Yeah, how does the energy get from, you said electron "A" and electron "B" let's say. How does electron "A"
3623	Through the collision
I-1	Okay. Through the collision?
3623	Yeah.
I-1	Okay what, when you say collision, what, describe that. When you say collision, what, if you had to use two atoms or two electrons or something, how would you
3623	You mean two balls?
I-1	I mean, however you think about it.
3623	I think of it as two balls.
I-1	Okay.
3623	When this one is moving faster so when it hits the second one, you

	may have a um, is that elastic or nonelastic collision where all the energy
I-1	It's one or the other yeah.
3623	Is going to get transferred from this to this one and this one will likewise transfer the energy
I-1	Okay.
3623	Onto the rest.
I-1	Okay. So you, you think, so you think about them actually physically colliding with one another?
3623	Yes.
I-1	Okay.

After students 5601and 6572 mention collisions of nanoscopic entities:

I-1	Okay. And you said something about collision, is that, you actually think about atoms hitting each other, how does that process work? How is this energy getting from one atom to the other? Kind of describe that process for me.
5601	Well, it's a transfer of energy, if two atoms are next to each other, you know, and that atom on the right has been excited and it's vibrating faster then it collides with the atom on the left side, and um, energy is transferred to the left side,
I-1	Um hmm.
5601	And both are vibrating and it just keeps on happening as it climbs with other atoms.
I-1	Okay. What I was looking for more of is a description of that collision.
5601	The collision.
I-1	I understand that you're thinking that they're, that collision
5601	Yes.
I-1	But what what does it really mean for those
5601	The energy to be transferred?
I-1	...collide. What parts are hitting, what what's going on? I mean when you think about collision, do you think the, how do you think about that? If you say collision, things are colliding, what does that really mean? I mean, you think about one car hitting another,
5601	Right.
I-1	That smacks it, I mean what
5601	That's what I, that's the order in more of what I'm thinking of, yeah, like you just saw my confusion, a car, obviously the car in front of you is at a stop and you hit it, it's going to start moving, so,
I-1	And that's really how you see the transfer of energy?
5601	That's how, that's kind of how I see it. That or like a ball hitting another ball, that's not moving and that ball moves and it hits another ball, like I just, I don't really, I don't really, I don't really know how to to explain it, other than that.

6572	There's going to be more collisions, there's going to be more, more collisions, uh,
I-1	Okay, what do you, what do you mean by collisions? What does a collision mean?
6572	Collision? Um, the atoms are getting excited, you know, on the, I don't know, I'm not too sure.
I-1	Well when you say collisions, what do you, is there anything that pops in your mind, can you visualize something on an atomic level that goes along with collision?
6572	If you have, like something in a, in a pan
I-1	Um hmm.
6572	In a close containment, you heat it up, there's more collisions on the, on the surface of the pan
I-1	Um hmm.
6572	That's what I meant by collisions.
I-1	But what, what's colliding? Let's talk about that.
6572	The molecules
I-1	The molecules? They're actually coming together, making contact?
6572	Yeah. Inelastic collisions.
I-1	Inelastic collisions? Okay. Um, does that same kind of thing, in your mind, help heat get through a material?
6572	Yeah.

Some students, even though they use the idea of colliding, did not know really what it meant:

I-1	How do they get their energy, so that the process propagates through the rod like we saw?
4991	Well, one excited atom would collide with another one, which would excite it.
I-1	But how, how, how would it do that?
4991	By transferring whatever made it excited, … I'm not really sure transferring is the right word, um,
I-1	Okay. Say I got, I have an atom here, it's been excited, has excited electrons like you describe. Next door, I'm in the crystalline structure in the metal, how does this particular atom get its energy to this particular atom? How would that happen? How would the energy get from here to here?
4991	I don't, I just, I mean it would transfer it somehow.
I-1	But not real sure about how that would happen?
4991	No, but through the bonds.
I-1	Okay. Through the bonds?
4991	Okay.
I-1	Okay, so
4991	I don't, I don't really remember … how it would transfer.

It is apparent that students have many particulate views of the interactions that take place in order for heat transfer to take place. What is even more interesting is how many students continue to rely on concepts associated with the description of kinetic molecular theory, where atoms or molecules in a gas are likened to balls that collide in order to provide a simply model of the process.

Expert Views on PNM:

In order for conceptual change to occur, there must exist a correct scientific view. This correct view is what establishes the body of knowledge that students' conceptions must contain in order for the educational process to be successful. To establish the correct scientific view for a particulate description of how heat transfers through a material, a theoretical physical chemist, three experimental physical chemists, and a chemical engineer were interviewed. All of the interviewees had experience teaching thermodynamics at four-year institutions. In the case of the chemical engineer, the primary area of expertise was in transport processes. The interviews were conducted in much the same manner as the students that participated using a similar interview script. The primary difference came in the fact that the experts were asked to comment on the appropriateness of the responses that the student participants had provided. Each expert was also asked to explain the process demonstrated in the Pasta Lab as if they would explain it to a class of thermodynamic students. There is common agreement with the mechanism that is described in terms of vibrations and collisions. Each expert identified the increased motion of the atoms or molecules as heat energy is transferred to the rod as a valuable concept:

Professor 1

I-1	And when they describe that motion, how, what should they describe?
P-1	Um, well, I would expect them to possibly, we like to do a little ball-bearing shaker thing that showed a jiggling of something that is supposed to resemble a solid, so it would be nice if they had some kind of picture where molecules were sort of arranged in an orderly way, started jiggling more and so spread out because of that, or that's in terms of the expansion part. I mean expansion isn't necessarily relevant for this particular demonstration, but if they're going to bring out

	expansion I would like them to have that picture.
I-1	Okay. Now, students at the introductory level, when they use terms like atoms move and then I get them to describe to me that motion, what kinds of things should they be describing?
P-1	Oh I see, so you would like the word vibration perhaps or, I mean I think the ideas are here, in the sense that the atoms don't move a whole lot, so presumably they're thinking about jiggling, vibrational kinds of motion
I-1	So vibrational?
P-1	Yea.

Professor 2

I-1	Yea. When you talk about motion with them, what types of things are you describing to them (the students) as being the motion that's increasing as temperature is, as temperature is increasing, kinetic motion is increasing, what do you describe that motion as?
P-2	Um, the, in the concept of the Physical Chemistry course, the initial introduction would be when we talk about kinetic molecular theory as a model for gases, so I would expect that would be the anchor on which students would think about temperature. Then we also discuss the Boltzmann concept of temperature distributions, in the context of vibrational energies and rotational energies becomes the quantum of this class, and so
I-1	Okay.

Professor 3

I-1	Um, what about motions of the atoms or molecules, what should they be able to tell us about that?
P-3	You mean
I-1	Because they're, well
P-3	You mean about the fact that they're restrained within the system
I-1	Right, instead of having,
P-3	I didn't make that very clear, when you're developing the model, I think you have to give them a model that here are all of these, let's call them atoms for convenience right?
I-1	Okay.
P-3	Here are all these atoms, right, and because there are attractive forces between them, they arrange themselves in patterns, right, and that within this, as long as the the rod is at some temperature, right, the atoms are constrained by the forces between them, that they can only move through small motions, that they can only vibrate about it, given position, and only rarely will one of them be able to break loose and travel, in fact that will hardly ever happen, so you have to give them that picture of the rod as an assembly of self restrained atoms, uh, I was, I was trying to think um, the the the thing that's very difficult um, uh to get across without resorting to some sort of quantitative reasoning, which is

	too messy at their level, is the idea that uh, there are forces between the molecules and that they are constrained about about their position um, along time ago, I would have, I would have probably made a joke about what happens when you have males and females at the dance.
I-1	Um hmm.
P-3	Right, they are attracted and they tend to to remain in a, and it's only when there's some extraordinary energy that the particles leave the assembly
I-1	Right.
P-3	You can't develop that very well and it's not politically correct to refer to those sorts of things. Um, I think that the other thing would be to try to construct some sort of visual simulation, to help them,
I-1	To help them build that mental model
P-3	So that you could see the atoms all sitting still

Professor 4

I-1	Um, I guess where we'll start is explain, if you had to tell one of your students, explain the demonstration that I did and you had to explain how heat got from the water, allowed the butter to melt, how would you explain it to them?
P-4	How would I explain to my students how it would happen?
I-1	Um hmm.
P-4	I think I have explained it, that basically there's the traditional mechanism operating in all, in all the rods was the fact that you have nuclear motions that get excited and then so molecules as they vibrates, vibrations are excited and they bump, each excitation spreads, the collisions and rises up through the beam, but then the difference and the reason you guys ask them about conductivity electrically was that for, when you have a metal, a conductor, small amounts of energy can excite electrons as well, so then the electrons are free to flow and actually spread through electronic collisions if you'd like, the energy, so you have another pathway, so you have more than one pathway for things that are metallic due to that extra degree of freedom that can be excited by small amounts of temperature.
I-1	Okay.
P-4	I probably was quite less formal.

Professor 5

I-1	Okay, for the process of heat getting through a rod, you had to explain that to a physical chemistry student, how would you explain that to them, how would you say that heat gets from hot water up to the butter to melt the butter?
P-5	Um,
I-1	Without using a bunch of math, because it's
P-5	Yea, I would probably qualitatively tell them that you know, and maybe I

	would start with my thermodynamics background, say, if we were going to transfer energy between gases how would we think about it?
I-1	Um hmm.
P-5	Well we think about it through maybe collisions, if the atoms actually have to collide with each other to transfer electrons, and that's because they are single particles, they are individual particles.
I-1	Um hmm.
P-5	When we're transferring heat and solids though, we know that we don't have that diffusion anymore, so the atoms you know, atoms are not moving around and they don't have kinetic energy now because they've trapped them in the solids. But what solids do have, is that solids, you know we think of solids as being rigid and they don't move, but in fact they do move
I-1	Um hmm.
P-5	And I think I would try to explain to them that um, if this was P. Chem I would I would teach them about you know, we've seen that individual molecules have vibrational modes that they, the water molecule has modes of vibration and if I put energy into those modes, I can make those modes change
I-1	Um hmm.
P-5	In solids, we have the same phenomena, but we have larger scale motions and we would call those whole nonmodes or lattice modes, that even solids are not static, they're, they're dynamic and there are still motions among those
I-1	Um hmm.
P-5	And if I start heating it up, those modes are low enough in energy that if I put in thermal energy I can get an increase in frequency of those modes and that's how pretty much the heat is going to progress up the rod, as you're going to get transfer through these thermal modes, all through these full nonmodes up and down the rods, and I would probably try to explain to them more that way, and I think if I was going to do it, I would show them a little bit more about solid structures and how solids really work, unfortunately we don't do so much of that, but
I-1	Okay. If you had to explain, okay, I've got these motions within the solid material, but how actually does energy get from one copper atom to the next for a copper rod.
P-5	Yea I would say it doesn't go to one atom to the next. Uh, what I would say is that, you have to understand that, that the atoms in the rod, all together make up a lattice, and so we, when we think of energy, and thermal energy inside moving up and down the rods, what we're really looking at is um, is energy transfer between collections of atoms or collections of molecules within the solid, so you're really looking at the transfer of energy along that rod, but along the collection of atoms, so I don't think it's, I wouldn't tell them that you're transferring energy from an atom to an atom because the atom does not have any capability of retaining thermal energy so the heat capacity has nothing to do with an

	individual atoms property, but it had to do the collection of them together
I-1	Um hmm.
P-5	And how many modes of motion do they have to distribute the energy.
I-1	Okay.
P-5	And I guess I would tell them that energy, you know if you think about this from a from let's say a collection of particles moving, so let's say we had a whole collection of the moving together
I-1	Um hmm.
P-5	I'm trying to think of a good example of something like that but I can't, but you know if I have a whole bunch moving and I put energy into one and I get them moving faster, these motions are all coupled to motions all the way down, so if one starts moving they all have to, they are all coupled, the full nonmodes or, a freshman wouldn't understand that, but kind of a vibrational band or vibrational movements within the solid are all going to be coupled together, they have to be, they're all connected.
I-1	Right.
P-5	So, you're kind of putting in kinetic energy so you're getting some fluctuation, but that's going to transfer all the way down, because all the motions have to be coupled together, because you don't have just one atom, I would try to get rid of the idea that one atom you can heat up with a, with a
I-1	Propane torch
P-5	Yea, that you can't excite one of them because that energy is way too low to do anything to the atom, what you want to do is you want to, to get this kind of heat, I mean hot water the energy is so low that what you're looking at is low frequency, low, you know, you're just looking at distortions, and you're getting a progression of distortion along really what you're looking at I would think.
I-1	Okay.
P-5	That's my generic atomic level detailed answer to that.

Asked specifically about students using the concept of collisions as a mechanism, one expert said:

I-1	When you say collision, what do you mean by collision?
P-4	Well for nucleus, degrees of freedom, it's just the fact that you have, as the nuclei moves it carries the electrons with them so there's electron to electron interaction directly, it's repulsions due to electrostatic propulsion and through other mechanical effects I would tell them.
I-1	Okay.
I-1	When you, when you use words like collision
P-4	Um hmm. It's a repulsive interaction.
I-1	Do you describe it that way
P-4	Yeah.

I-1	Or do you actually just use the word collision and …
P-4	… we talk about electronic, intramolecular interaction.
I-1	Okay.
P-4	We try to, it's hard because you try to give them the perspective that they see when, you know you draw a simple potential energy pair, there's a lot of inner potential energy and then when you draw one of these simple guys, there's a lot of energy, this is what you normally would show for some simple diatomic system for example

What's interesting about the expert descriptions is that terminology and the underlying conceptions represented by the terminology is much like that used by the students to describe the process. Linn and Muilenburg [111] found similar results when they asked physicists, chemists, and engineers to explain why a wooden spoon is better than a metal spoon to stir boiling liquids in a pot. Students, like the experts, do not engage in much discussion about the particulate interactions involved in heat transfer, however, the experts expressed in the interviews that this level of detail is something students should know. Conceptual change hinges on the idea that there are correct scientific concepts and in order for educators to affect the conceptions of their students, the correct scientific concepts with full descriptions need to be utilized. Cognitive levels do play a role in what is appropriate to teach students, however, at the college level students are at a cognitive level appropriate to understand full scientific explanations involving particulate nature of matter.

SUMMARY

Conclusion

How can students' concepts about PNM be improved?

The key to the answer is that teachers are themselves learners and are likely to also have many of the same conceptions that their students have. Dorothy Gabel, K.V. Samuel, and Diana Hunn [17] investigated this very notion. They studied a group of prospective elementary teachers to see what their views were of the particulate nature of matter. The authors' premise was that because elementary level students are increasingly being exposed to PNM concepts, the teachers should have proper PNM concepts that they can relay to this level of student. "The ability to represent matter at the particulate level is important in explaining phenomena or chemical reactions, changes in state and the gas laws, stoichiometric relationships, and solution chemistry." To evaluate teacher's views of PNM, the authors developed a 14-item Nature of Matter Inventory test that showed pictures of matter with atoms and molecules depicted as circles of various sizes and shades. The authors also used a battery of other tests, which included a spatial visualization test, and a questionnaire so that chemistry and mathematics background could be accounted for. The additional tests were used to correlate individual performance on the Nature of Matter Inventory. The responses were analyzed using a predetermined list of attributes that the subjects should account for when complete the Nature of Matter Inventory. These included: (1) Conservation of particles, (2) proximity of particles, (3) orderliness of particle arrangement, (4) location of particles in container, (5) constancy of particle size and shape, (6) particle discreteness, (8) arrangement of products, and (9) bonding. The findings were similar to the findings of other

research conducted and discussed elsewhere in this paper. The preservice teachers believe that atoms expand as they change from liquid to gas phase, indicating that as heat is added to an atom, the atom itself increases in size. Particles in gas phase were drawn by the presevice teacher to be in an orderly arrangement versus a disorderly fashion. The preservice teachers also fail to show particulate conservation of matter after decomposition takes place, reemphasizing the belief in a continuous nature of matter versus that of a particulate makeup of matter. The authors make a case that if the subjects have problems with the concept of PNM, then they too will have difficulties representing to students both physical and chemical changes. The authors suggest that "an increased emphasis on the particulate nature of matter in introductory chemistry courses and the careful representation of particles by chemists, when they are used in instruction, might bring about not only an increased ability to solve chemistry problems, but it may also help to make chemistry more understandable by providing the framework underlying the discipline."

The problem of instilling a correct concept of the particulate nature of matter seems to be of great importance, considering it is a concept at the center of understanding chemistry. The problem seems to be far reaching as indicated by the reviewed literature. Students at all levels have difficulty internalizing the concepts, at least internalizing the concepts that are scientifically acceptable and correct. Teachers responsible for ensuring that students leave a course of study have the same difficulties. They hold incorrect concepts and then further reinforce the misconceptions as students learn from them. There is not an easy answer to this problem. Time must be spent on student instruction to try and correct the concepts that they form both by formal instruction and natural interactions with their environment. It is not an easy task, but educators have to start the process, because as they say, even the longest and most difficult journeys start with one step.

"Even though chemistry education research has identified misconceptions for almost every topic taught in introductory courses, it is thought that the majority of

instructors are not aware of these and do not utilize ways to counteract them"[87]. Misconceptions are often viewed in this light as concepts exhibited or employed by students that do not parallel those commonly used by the scientific community.

Often students in general or introductory chemistry courses do not gain a firm grasp of PNM because of several factors and subsequently find it difficult when they are required to apply it. It is thought that this difficulty with understanding PNM carries over to other chemistry concepts that are based on the behavior of particles. Students who do not make conceptual sense of PNM will have difficulty understanding other major concepts in introductory chemistry and later in advanced chemistry courses.

Implications for Chemistry Education

A chemistry instructor's overall task during a student's formal instruction is to establish ways for students to visualize and understand phenomena that are impossible to observe first hand. The instructor's role is important in that the instructor is in a position to provide for situations which allow the students to build theories based on their own understanding of phenomena and use these to build students' knowledge toward that which is scientifically accepted. Scientifically acceptable knowledge is key in facilitating the conditions of conceptual change; If educators expect students to have scientifically acceptable conceptions then the educators must be familiar with existing conceptions and know how to lead the students through conceptual change.

An additional implication is the lack of students' use of mental models in order to describe the transfer of heat energy through the various materials. Harrison and Treagust [59] looked at secondary students' mental models of atoms and molecules and describes how students come to form generalized mental models of atoms and molecules based on personal experience. The authors state after Kline that "despite the desire to produce mental or analogical models of abstract objects and processes, the belief that we can do so is a myth". The main reason

given is that there is not a direct correlation between complex mathematical descriptions and physical models meant to represent reality. Where practicing scientist use mathematical models to advance understanding, teachers are left with imperfect models and analogies to relay abstract ideas best described by mathematical means. As a result, students incorporate less than complete models into their knowledge framework and use them to further learn about and then describe phenomena.

It is evident that the same held true for the subjects of this study, they tend to use incomplete models or use models incompletely in order to describe heat transfer. Many of the physical chemistry students interviewed stated that they believed it would be easier to use the math to describe a process if they were able to imagine what was physically happening. In other situations students trying to describe what was happening during heat transfer said that they could not imagine what was going on but that they knew formulas they could use to describe what was taking place. This provides evidence toward the idea that students should be provided with situations in the classroom where they are required to form mental models of phenomena discussed in class. This is even more true for situations in thermodynamics courses where the phenomenology is described in mathematical terms. Bodner [43] states that social knowledge can be learned through direct instruction, however, "physical and logico-mathematical knowledge cannot be transferred intact from the mind of the learner. The constructivist model therefore requires a subtle shift in perspective for the individual who stands in front of the classroom". The instructors should reflect on how the math, as a model, reflects physical interactions on a particulate level to allow students to engage in the activity of forming their own useful models. Linn and Muilenburg [111] suggest that "effective science instruction helps students to sort and distinguish among a multitude of ideas. Its purpose, then, is to offer the best set of models for the students to work with, to encourage students to compare these models to their own, and to set in motion a process of analysis that becomes a lifelong habit."

This idea of allowing students to reflect on how their models compare to the models relayed by the instructor is an integral part of constructivism and conceptual change. It provides the environment in which active construction of knowledge takes place. As discussed elsewhere, the formation of knowledge is not a passive process. It is also through this process that a student becomes aware that there is a problem with the way (s)he might be thinking. As Bodner [43] states, "Students need to know that a problem exists before they are willing to accept an explanation".

The take home message in summary is quite simply, in order to facilitate students learning, there must be two-way communication between the instructor and student. The instructor must present correct scientific truths appropriate for cognitive ability. As well, the instructor must also listen to the concepts relayed by the students. The present author agrees with the benefits of open communication in education, relayed by Bodner [43], which summarizes a constructivist approach that may improve the successful incorporation of correct particulate concepts:

> "This dialog shows many of the signs of a constructivist teacher who questions students' answers *whether they are right or wrong*, insists that students explain their answers, focuses the students' attention on the language they are using, does not allow the students to use words or equations without explaining them, and encourages the student to reflect on his or her knowledge, which is an essential part of the learning process".

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APPENDIX

Figure Two: Questions and statements contained on cards used for physical chemistry student interviews for question one

Q1: **What is the path heat travels in getting from the hot water to the butter?**
Q1R1. "It travels up the rod for the most part, some is in the steam."

Figure Three: Questions and statements contained on cards used for physical chemistry student interviews for question two

Q2: **All of the materials in this experiment (and everywhere) are made of atoms. Describe what you think is happening on the atomic level as the heat travels from the hot water to the butter.**
Q2R1. "I think the atoms in the rods eventually become closer together. As the atoms get hotter, they expand. So when one hot atom touches a cool atom, the hot atom heats up the cool atom until the atoms are heated enough to work their way to the top of the rods and melt the butter."
Q2R2. "The atoms are being heated up and the energy is passed through electrons through each of the mediums until the butter warms and melts down the rod. The atoms in the butter spread out and disperse because it has reached its melting point."
Q2R3. "The heat is exciting the atoms in the rods causing them to move slightly more than they do at room temperature (this is only slightly since atoms in solids do not move a whole lot.) When the rod atoms move more the rod heats up and transfer the energy to the butter. The butter atoms then get excited and begin to move. Because butter has a lower melting point than the rods do, [the butter reaches its melting point], it melts."

Figure Four: Questions and statements contained on cards used for physical chemistry student interviews for question three

Q3: Why did the pasta fall for some of the rods earlier than for other rods? (Please explain this both in general terms and then at the atomic level as you understand it.) Include a list of the material in order that the pasta fell from fastest to slowest). (Discount the list for interview)

Q3R1: "I believe that the atoms are closer together in the copper rod than in the iron rod, therefore heat energy transfers easier in the copper rod."

Q3R2: "In the rods that had the fastest fall times, the atoms were further apart and had more room to move around. In having extra room the atoms can move faster and can pass more energy which increases the temperature of the rod faster.

Q3R3: "Different materials have different thermal conductivities. The ones with higher thermal conductivities get heated sooner, which makes the pasta to fall fast."

Q3R4: "The specific heat for each of the rods was different. This means that it takes less time for a given mass of a material to heat up if its specific heat is low and it takes more time for the same mass in a different material to heat up.

Figure Five: Questions and statements contained on cards used for physical chemistry student interviews for question four

Q4: Would the same rods that seem to be good conductors of heat also be good conductors of electricity? Why or why not?

Q4R1: "...atoms that pass one type of energy will also pass another equally well...excited atoms pass energy from atom to atom."

Q4R2: "The good conductors for heat have lots of electrons and they will conduct electricity well."

Q4R3: "I don't think so because heat transfer is related to the transfer of energy through the whole atom and electricity transfer is related to the free electrons that transfers from one atom to the other."

Figure Six: Sources of PNM misconceptions

Author(s)	Date	Method	# of Subjects	Age or Grade	General Misconception	Code
Abraham &Williamson [3]	1994	OE Written	300	9th,11-12th, College	1. lack of conservation of atoms.	G1
Ben-Zvi, Eylon, & Silberstein [7]	1986	OE Multi Written	PI,300 PII,1078	15 years av.	1. No distinction between properties of a substance and those of a single isolated atom.	G2
					2. An atom of gas can be compressed.	G2
					3. An atom of gas expands when heated.	G3
					4. Gas atom larger than solid atom.	G4
					5. Single atom can conduct electricity.	G2
Ben-Zvi & Gai [49]	1994	Multi-Ex Written	170	10th	1. No change in atomic or molecular motion as heat is added to a system.	G6
Brook, Briggs, & Driver [10]	1984	OE Written Interview	300 30	15 years	1. As temperature of a substance decreases, particle speed increases.	G46
					2. Decrease in temperature of a substance decreases the forces exerted between particles of that substance.	G7
					3. Application of macroscopic characteristics (size and temperature) to particles.	G2
					4. No appreciation of the intrinsic motion of particles	G8
					5. Particles expand and exert forces on each other upon heating.	G3

Figure Six (Continued):

					6. Misapplication of the kinetic molecular theory; solid state is likened to the gaseous state or to the liquid state.	G9
					7. Particles can move freely in a solid.	G9
Gabel, Samuel, & Hunn [17]	1987	OE Written	90	Preservice elementary teachers	1. No conservation of particles.	G1
					2. The enlargement of atoms as they change from liquid to gas.	G47
					3. Gas particles are arranged orderly in space.	G48
Griffiths & Preston [18]	1992	Interviews	30	12th, 16-18 years	1. There is only one kind of atom.	G10
					2. All the atoms in a molecule are the same	G11
					3. Heat causes molecules to expand leading to separation of molecules during melting.	G3
					4. The speed of a molecule is determined by its size.	G12
					5. The more space a molecule has to move the faster it will move.	G13
					6. Heat causes molecules to expand.	G3
					7. An atom resembles a sphere with components inside.	G49
					8. An atom resembles a solid sphere.	G14
					9. An atom looks like several dots/circles.	G15
					10. Electrons move in orbits.	G16
					11. Atoms are flat.	G17
					12. Matter exists between atoms.	G18

APPENDIX (CONTINUED)

Figure Six (Continued):

					13. Atoms are large enough to be seen under a microscope.	G19
					14. Atoms are larger than molecules.	G20
					15. All atoms are the same size.	G22
					16. The size of an atom is determined primarily by the number of protons.	G23
					17. Heat results in a change of atomic size.	G3
					18. Collisions result in a change of atomic size.	G21
					19. All atoms have the same weight.	G24
					20. Atoms are alive.	G25
					21. Only some atoms are alive.	G25
					22. Atoms are alive because they move.	G25
Haidar & Abraham [58]	1991	OE Written	183	11-12th (17 years average)	1. Lack of a model of interaction (attraction and repelling forces) between molecules	G50
					2. Belief that heat is a substance that can be attracted, absorbed, and can even take up space.	G26
Happs [86]	1980	Interview	41	10 -17 years Teachers & College	1. Generally many episodes of subjects associating macro level characteristics to particles.	G2
Lee, Eichinger, Anderson, Berkheimer, & Blakeslee [19]	1993	Multi-Ex Written Interview	15 classes 24 students	6th grade	1. Something exists between molecules in a substance	G18
					2. There is no motion associated with molecules in a solid	G8
					3. Molecules begin to move when external forces are applied	G51

Figure Six (Continued):

					4. Associated macroscopic properties to atoms and molecules	G2
Mulford & Robinson [79]	2002	Multi Written	928	1st semester college	1. Subject responses do not conserve atoms	G1
Nakhleh & Samarapungavan [55]	1999	interview	15	7-10 years	1. Macroscopic properties associated with microscopic entities	G2
Novak & Musonda [81]	1991	interview	239	1-12 grade	1. Particles or molecules become bigger when matter dissolves.	G27
					2. Particles or molecules get bigger, expand when heated.	G3
					3. Particle or molecular sizes, shapes and numbers change during melting or heating.	G5
					4. Different states of the same substances have differently shaped particles or molecules.	G28
					5. Particles or molecules shrink when cooled.	G5
					6. Particles or molecules gain weight when heated.	G29
					7. Particles or molecules get bigger when matter freezes.	G30
					8. Particles or molecules of solids are hard and that of liquids and gases are soft.	G2
					9. Particles or molecules can be seen with or without a microscope.	G19

Figure Six (Continued):

					10. Matter made up of something other than atoms or molecules	G31
					11. Solids do not have space between their molecules.	G32
					12. There is friction between molecules which generates heat.	G33
					13. Particles or molecules get soft when matter melts.	G2
					14. Molecules do not move in matter, especially in solids.	G8
					15. Particles or molecules move and make their own energy.	G34
					16. Particles or molecules in all states of matter possess the same temperature and pressure.	G35
					17. Particles or molecules move as a result of collisions between themselves.	G36
					18. Energy of molecules originate from gravity.	G37
					19. Molecules stop to move when substances are frozen solid.	G53
					20. Nothing holds molecules together in any given substance.	G50
					21 Molecules exist only in substances that can be broken down into powder form.	G38
					22. Solids are made of hard types of molecules.	G2

Figure Six (Continued):

					23. Equal volumes of any combination of phases of matter contain the same amounts of molecules.	G39
					24. Gases have more molecules per unit volume than other substances.	G40
					25. Particles or molecules of solids are smaller than that of other liquids and gases.	G41
					26. Solids have the largest particles or molecules followed by liquids and gases.	G42
Novick & Nussbaum [50]	1981	OE Multi-Ex Written	576	5-6th(n=83) 7-9th (n=339) 10-12th (n=88) sophomore college (n=66)	1. Subject across age groups have a static particle picture.	G8
					2. Attractive forces between particles of a gas increases and accounts for the decrease in volume.	G50
					2. The particle model only holds for gases; liquids and solids are continuous.	G43
Whiteley [34]	1993	Multi-Ex Written	182	16+ years	1. Heated particles expand.	G3
					2. Macroscopic properties attributed to microscopic entities.	G2
					3. Constant force(s) are required to keep particles moving.	G44
					4. Gas particles are light.	G2
					5. Gas particle collisions accounts for gas pressure.	G52

Figure Six (Continued):

					6. The speed of a particle of gas is dependant on pressure or volume.	G45

Figure Seven: Thermal conductivity example for copper

Thermal conductivity has the units of:

W/m K = watts per meter kelvins

Copper has the value:

385 W/m K

For the energy flow through a material:

(W / m K) (K / m) = W / m^2 W=joules (J) per second (s)

Where K/m is the heat gradient and W/ m^2 is the energy per area

For the copper rod used in the lab, hot water is poured over the bottom of the rod and the assumption is room temperature is 293 Kelvins, therefore the energy flow through the copper rod is:

(385 W/m K) {(373K –293K)/ .153m} = 1509.20 W/ m^2

The area of the copper rod used is:

Diameter=.006 meters Area = π (.003 m)^2 = .00942 m^2

(1509.20 W/ m^2) (.00942 m^2) = 160212.3 W or 160212.3 J / s